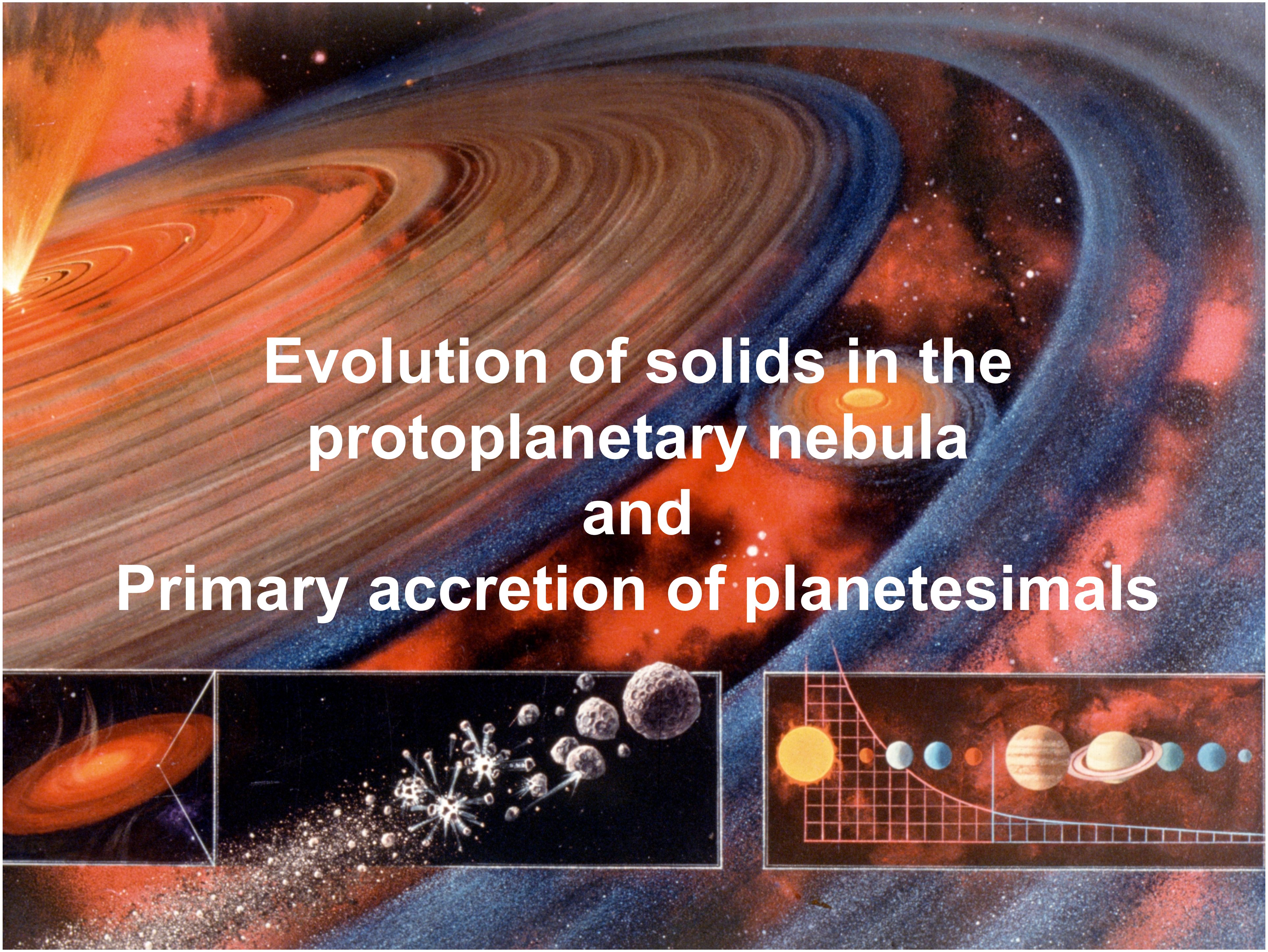
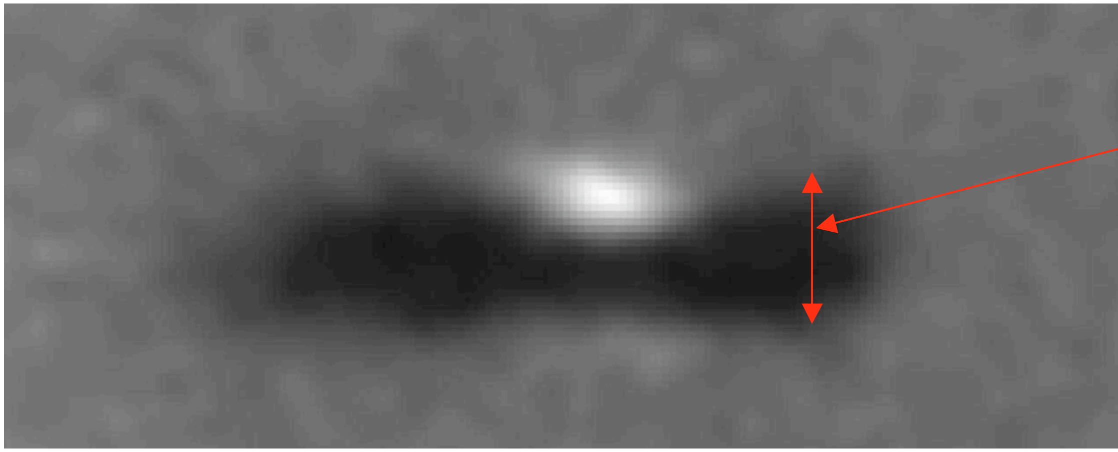
Evolution of solids in the protoplanetary nebula and Primary accretion of planetesimals

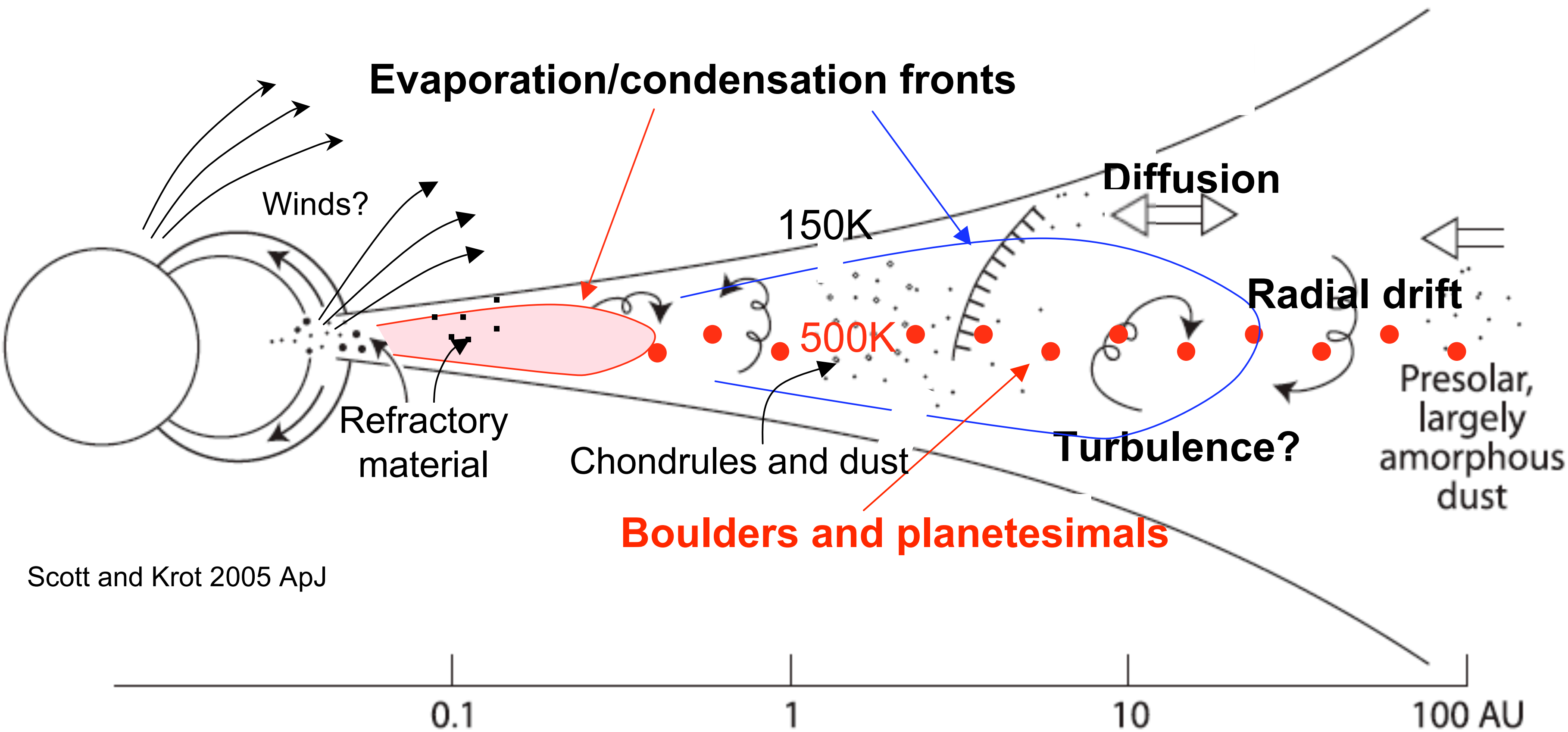




Remote observations tend to see 3-5 H, not near the midplane where primary accretion occurs

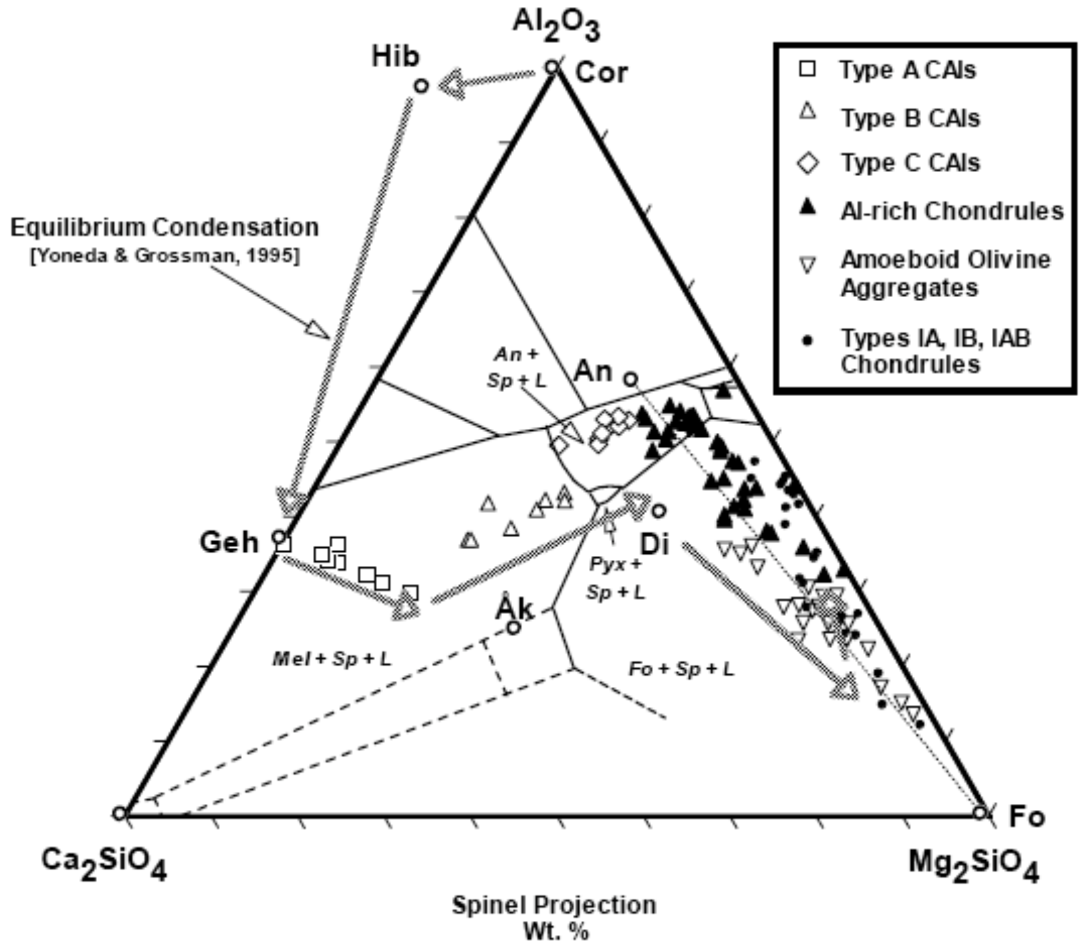
(10-100 km planetesimals)

(eg., Dullemond and Dominik 2004, 2005)



Scott and Krot 2005 ApJ

Communication between meteoriticists and astrophysicists is a serious problem



Communication between meteoriticists and astrophysicists is a serious problem

$$\bar{\rho}_p \frac{\partial}{\partial t}\bar{u}_p + \bar{\rho}_p \bar{w}_p \frac{\partial}{\partial z}\bar{u}_p = 2(\bar{\rho}_p v_p^* + \overline{\rho_p' v_p'})v_K/r - \frac{\partial}{\partial z}(\bar{\rho}_p \overline{u_p' w_p'}) - \frac{\partial}{\partial z}(\overline{\rho_p' u_p'}\bar{w}_p) - \overline{\rho_p' w_p'}\frac{\partial}{\partial z}\bar{u}_p - \bar{\rho}_p(\bar{u}_p - \bar{u}_g)/t_s, \quad (9)$$

$$\bar{\rho}_p \frac{\partial}{\partial t} v_p^* + \bar{\rho}_p \bar{w}_p \frac{\partial}{\partial z} v_p^* = -\tfrac{1}{2}(\bar{\rho}_p \bar{u}_p + \overline{\rho_p' u_p'})v_K/r - \frac{\partial}{\partial z}(\bar{\rho}_p \overline{v_p' w_p'}) - \frac{\partial}{\partial z}(\overline{\rho_p' v_p'}\bar{w}_p) - \overline{\rho_p' w_p'}\frac{\partial}{\partial z} v_p^* - \bar{\rho}_p(\eta v_K + v_p^* - v_g^*)/t_s, \quad (10)$$

$$\frac{\partial}{\partial t}(\bar{\rho}_p \bar{w}_p) + \frac{\partial}{\partial z}(\bar{\rho}_p \overline{w_p^2}) = -\bar{\rho}_p GMz/r^3 - \frac{\partial}{\partial z}(\bar{\rho}_p \overline{w_g' w_g'}) - 2\frac{\partial}{\partial z}(\overline{\rho_p' w_p'}\bar{w}_p) - \bar{\rho}_p \bar{w}_p/t_s. \quad (11)$$

Overview

Evidence from primitive bodies in our solar system

The importance of turbulence

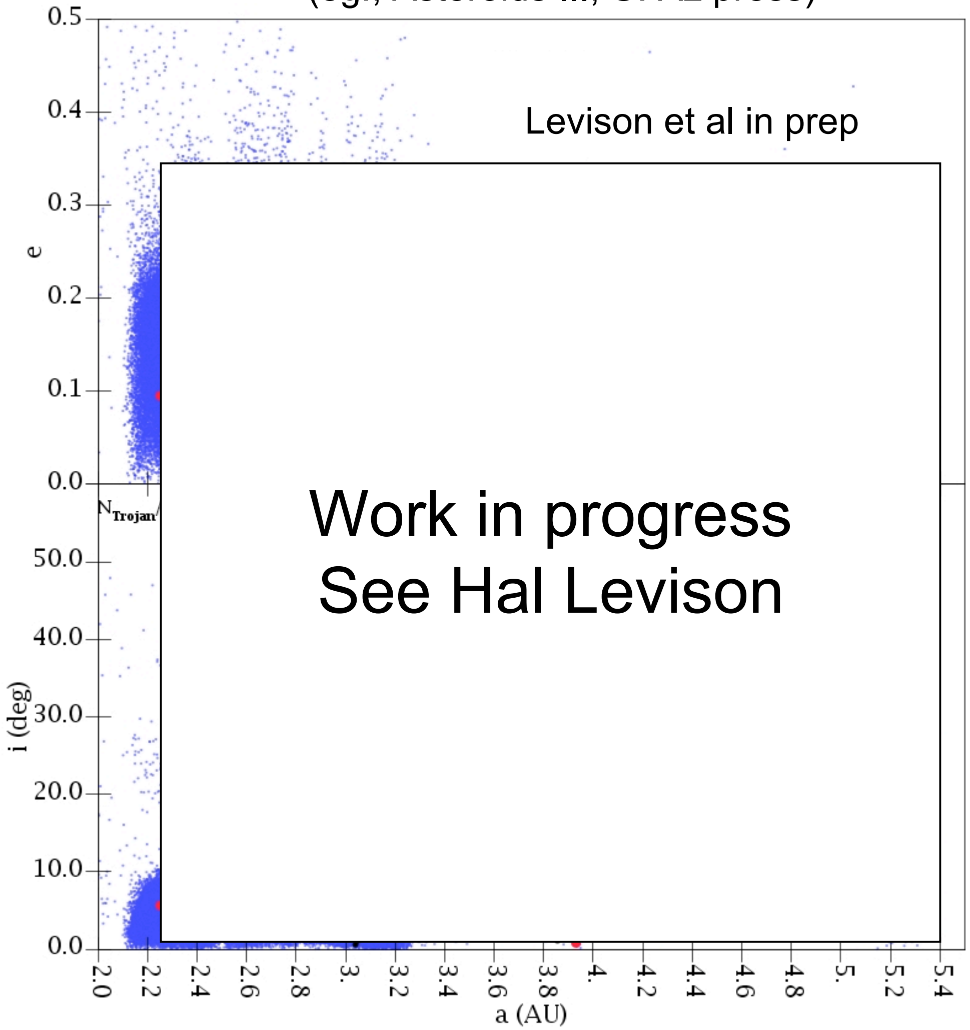
Particle collisions: sticking or disruption

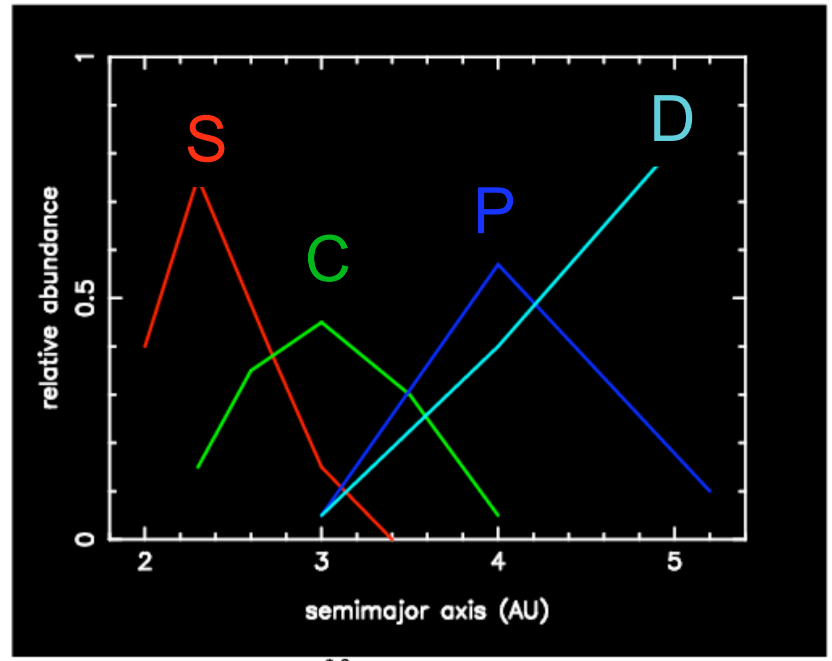
Radial drift of particles; evaporation fronts

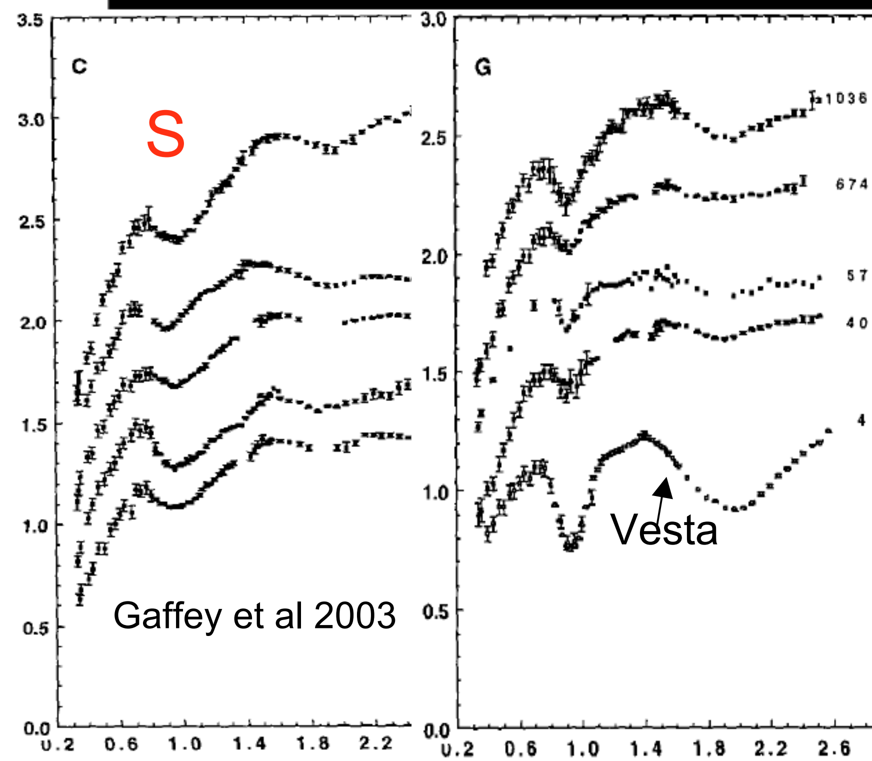
A scenario for primary accretion

Asteroids

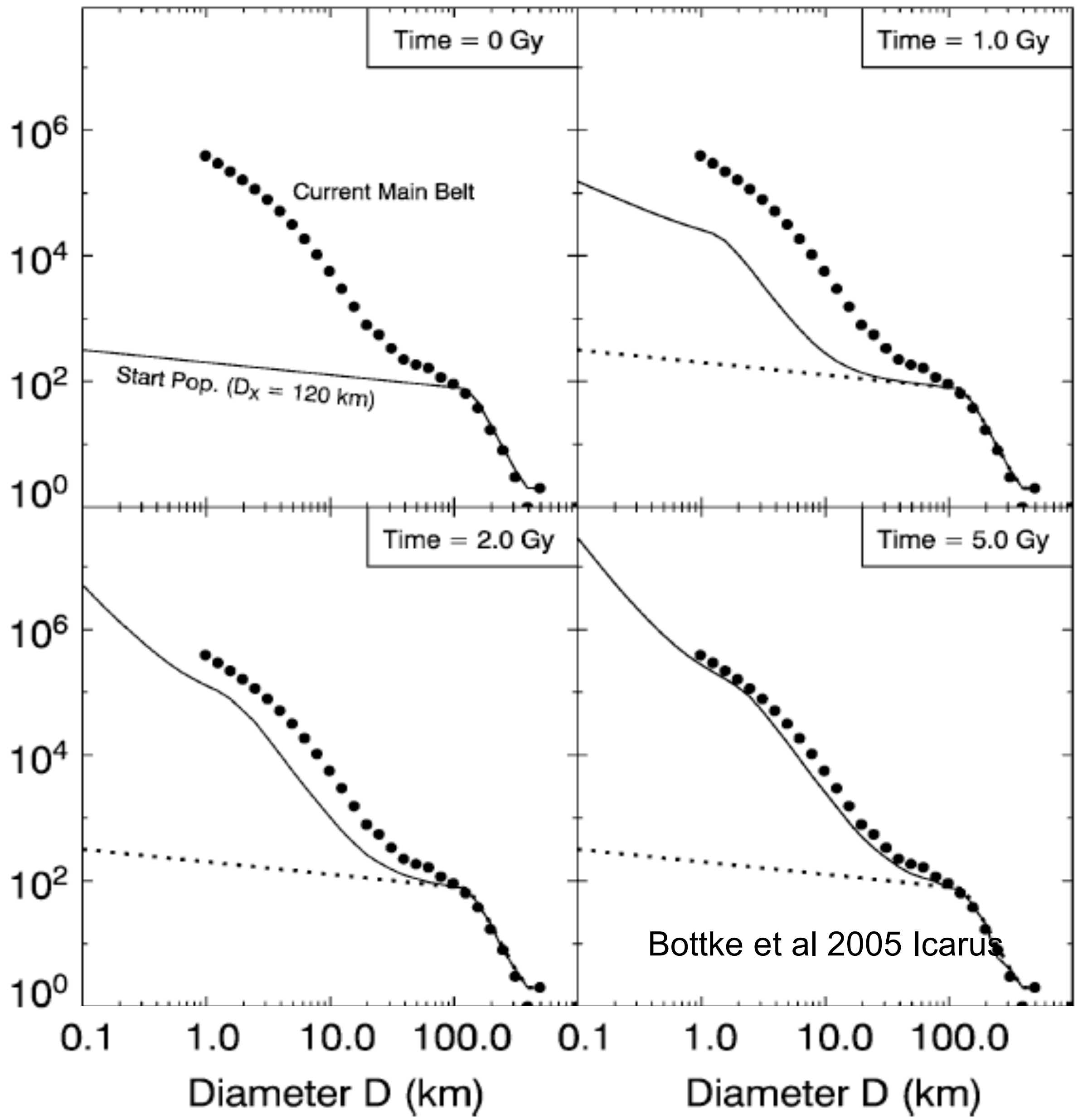
Radially zoned;
Some members formed elsewhere;
Few ever melted significantly
(eg., Asteroids III, U. Az press)







The violent youth of primitive bodies



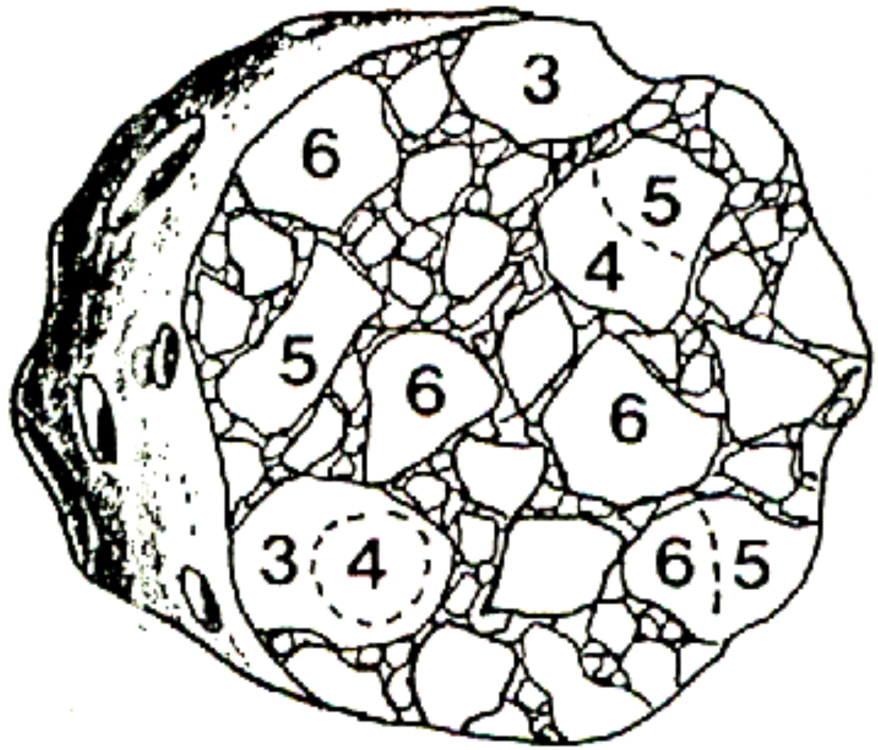
Collisional evolution
after nebula gas dispersed
and Jupiter formed
was unable to destroy
primordial 100km objects

(but nearly everything
smaller is secondary)

*Most primordial mass
was in 100-km objects*

D-type asteroids,
Kuiper Belt Objects
may have similar
initial size distributions

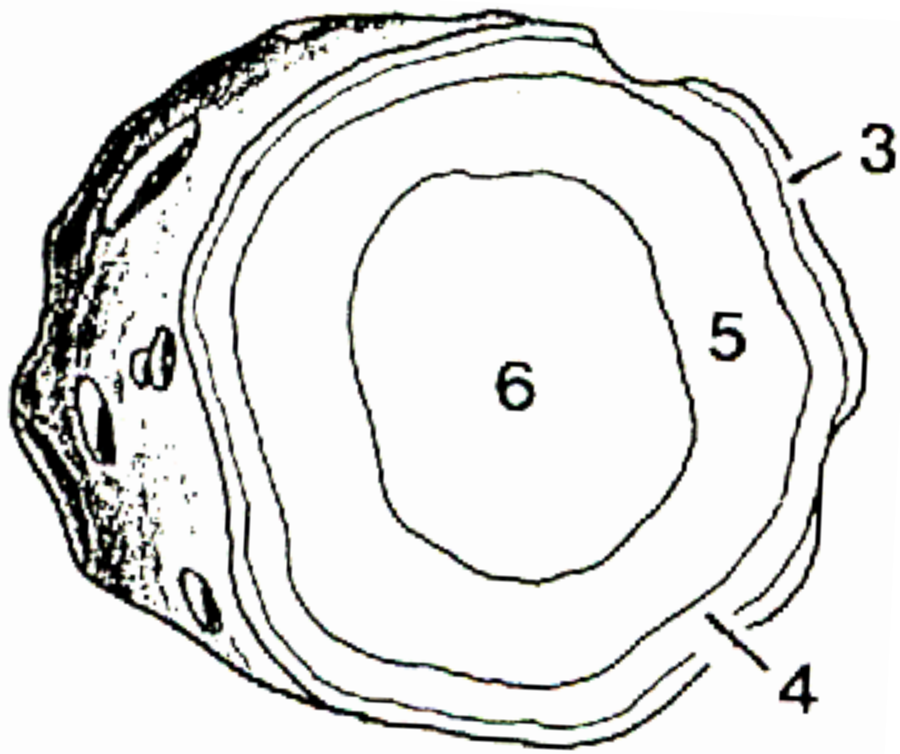
Post-primary-accretion collisional environment left many asteroids as rubble piles



Taylor et al 1987

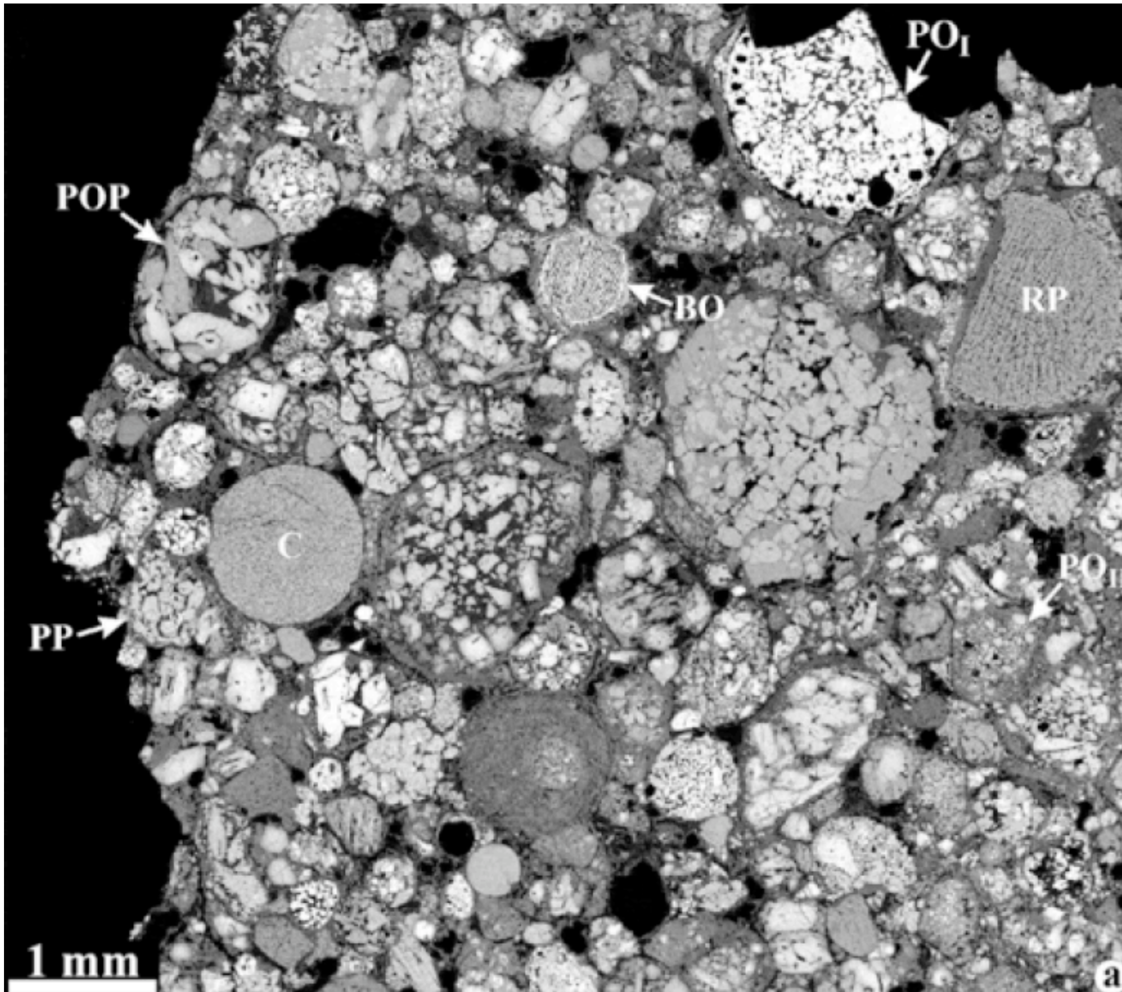
However, thermal alteration evidence suggests that pre-collisional object had more of an onion shell structure

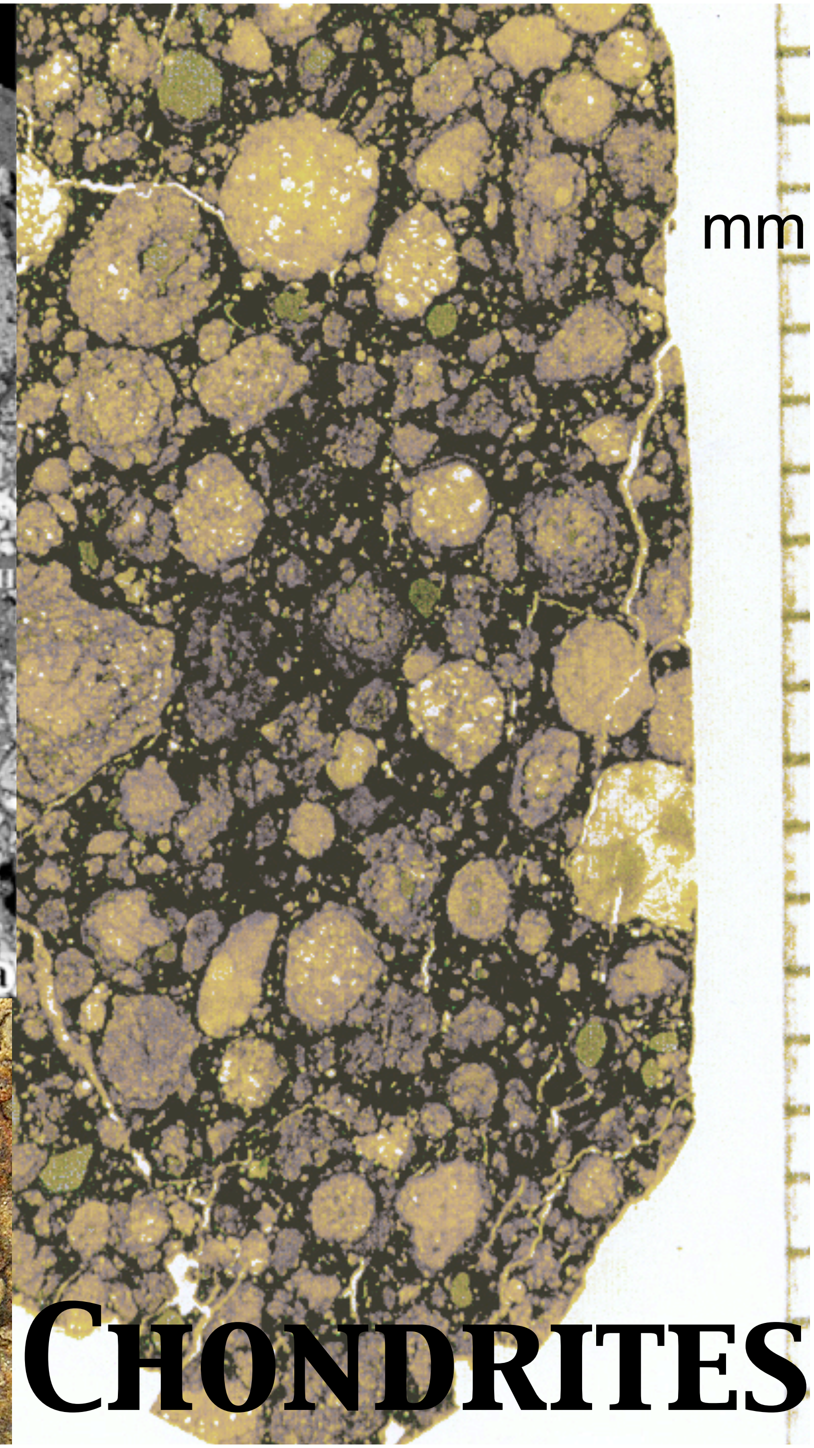
Initial contents were very homogeneous; thermal alteration baked inner material the most



Trieloff et al 2003

How to construct 100km asteroids (parents of groups) entirely out of “chondrules” with similar properties?





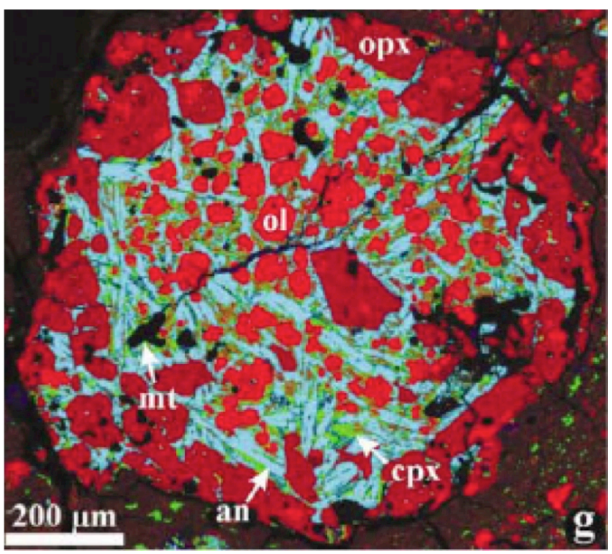
CHONDRITES

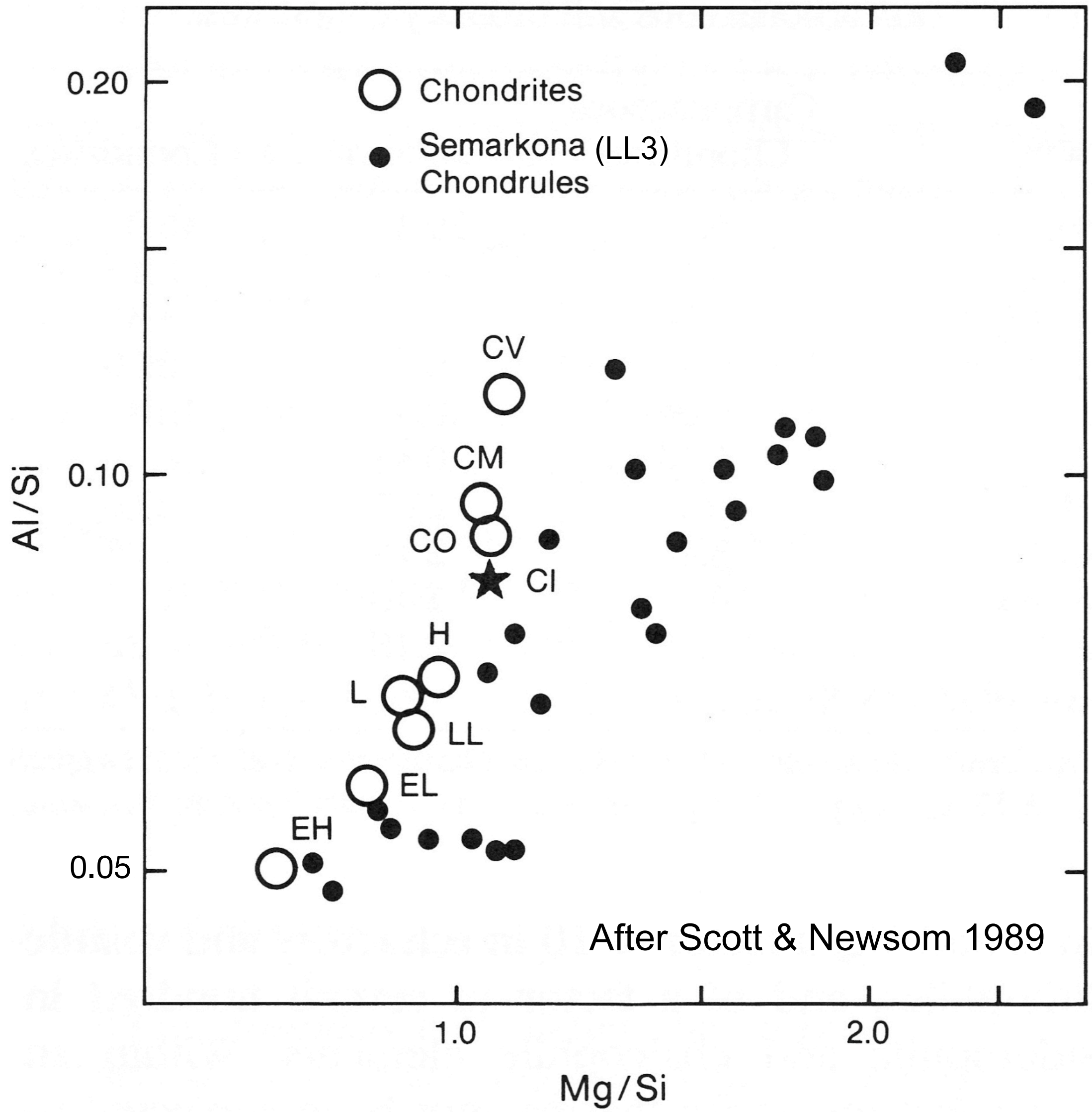
What properties define chondrite *groups*?

1. Chemistry and mineralogy

Major element variance between chondrules in a given meteorite exceeds variance between all groups

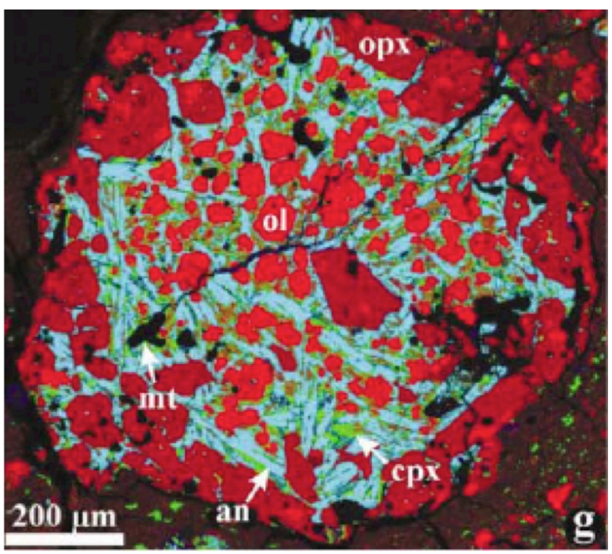
Groups represent “centroid” of a diverse local sample

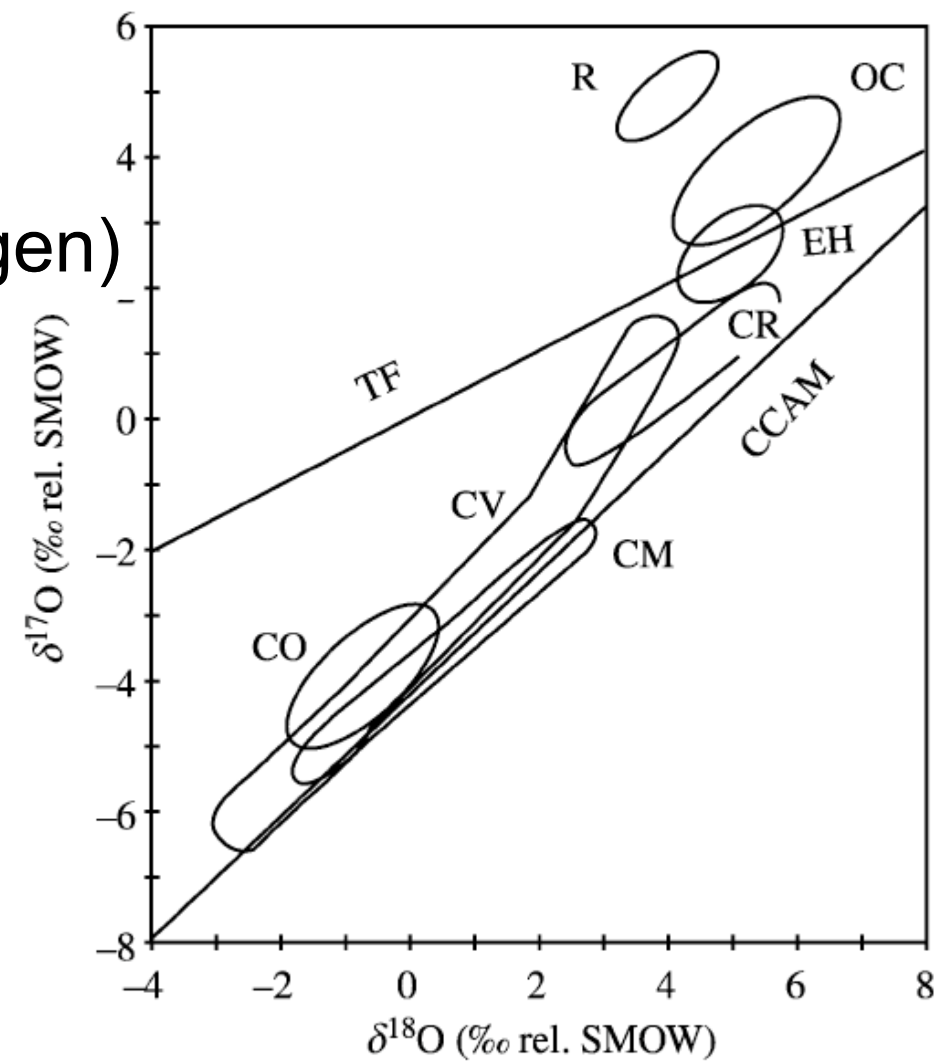




2. Isotopes (here, oxygen)

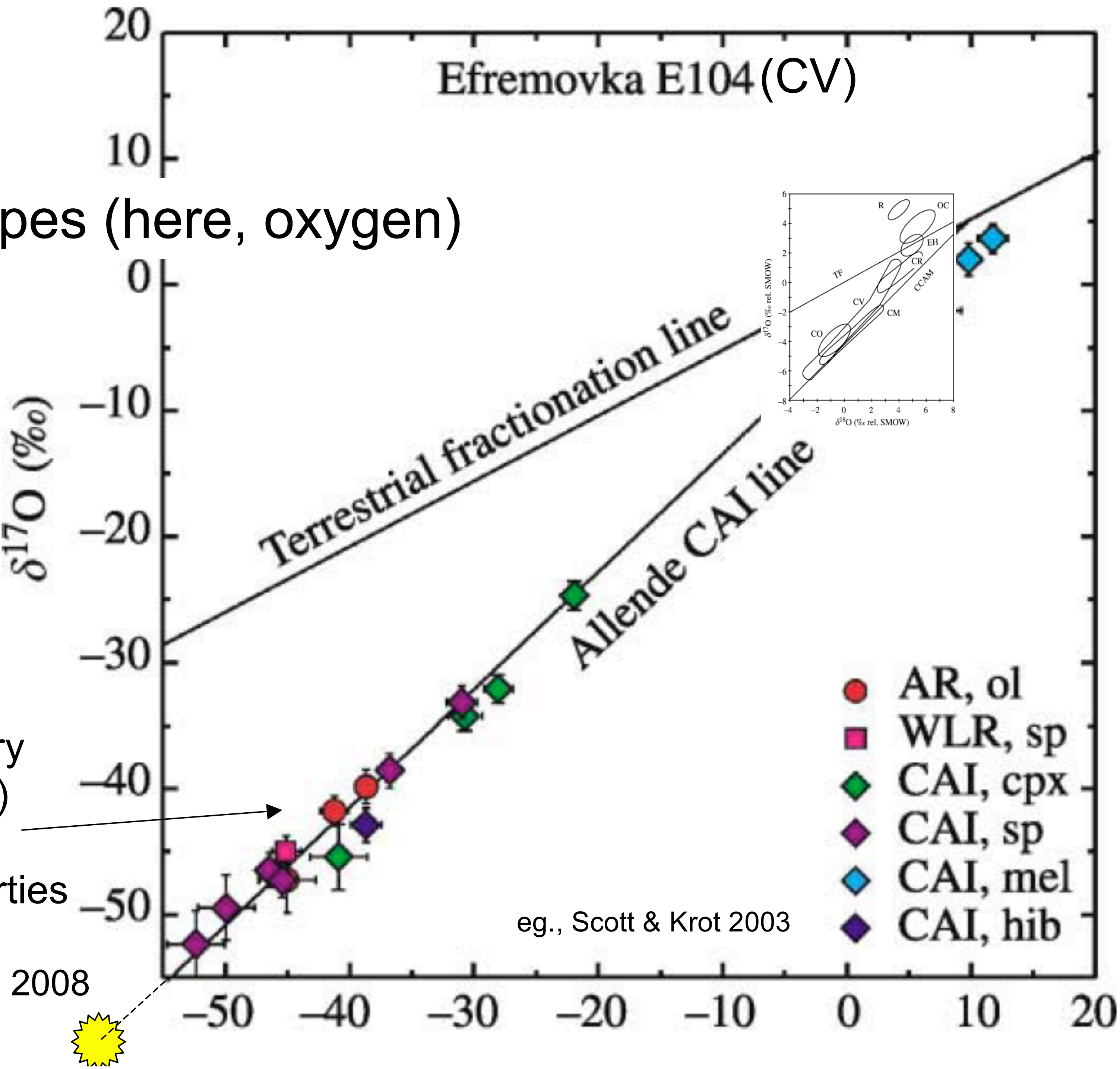
Isotopic composition of chondrules and bulk samples separate the different groups





eg., Clayton 1993 Ann Rev EPS

2. Isotopes (here, oxygen)

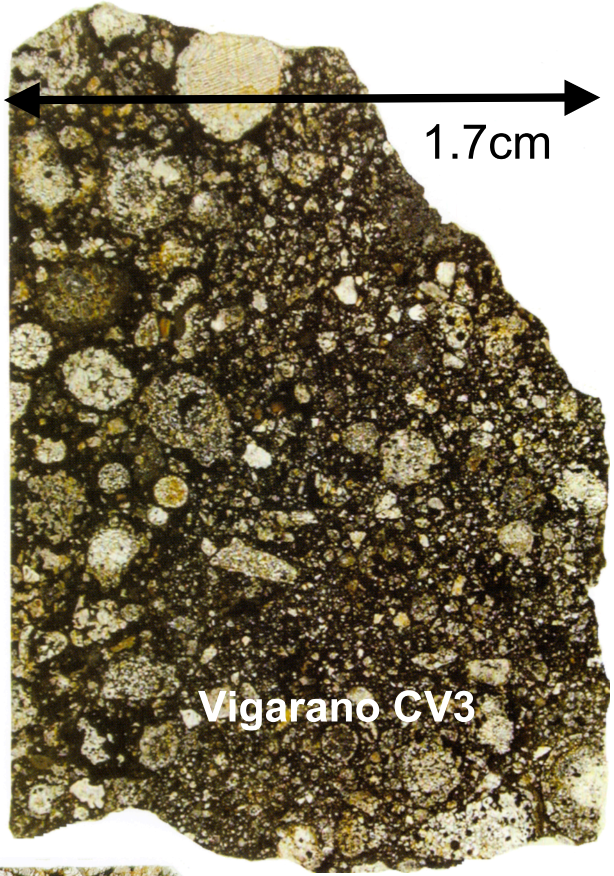


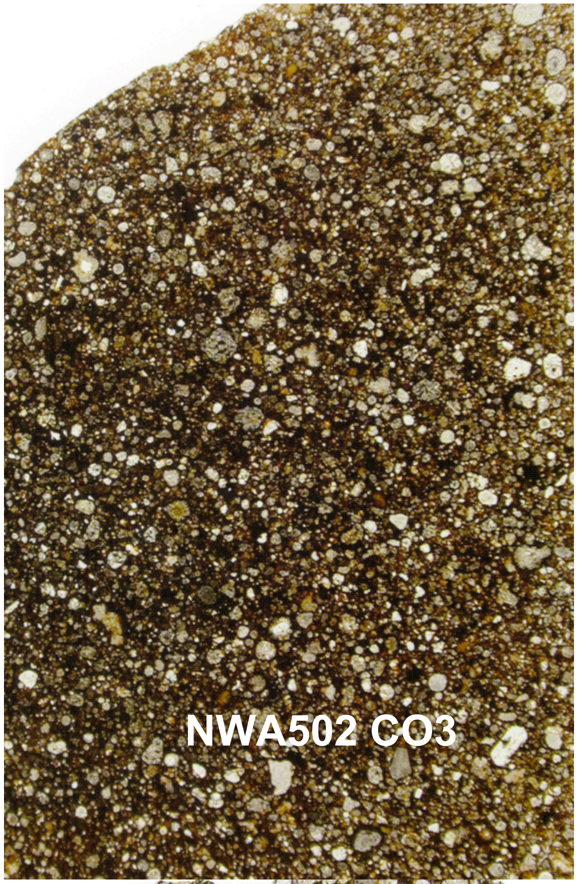
eg., Scott & Krot 2003

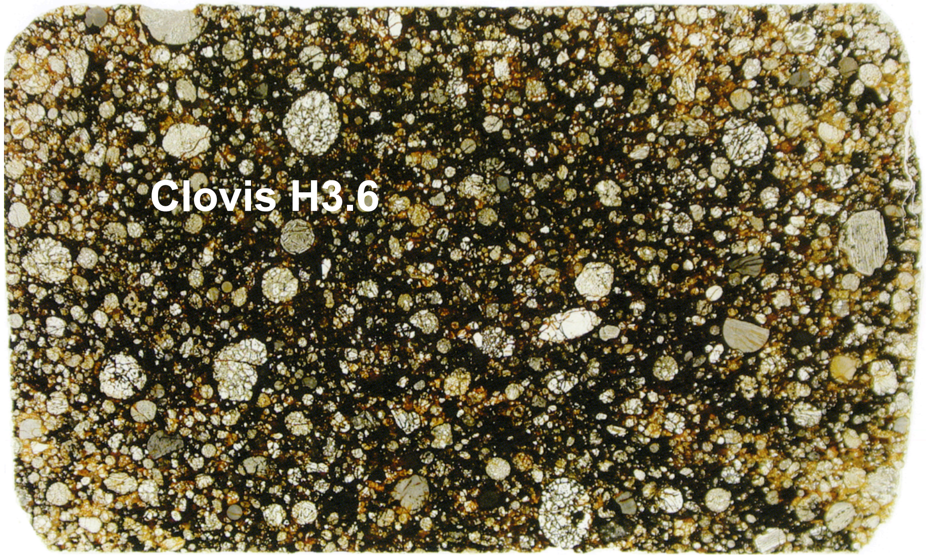
CAIs (refractory mineral grains) have different isotopic properties

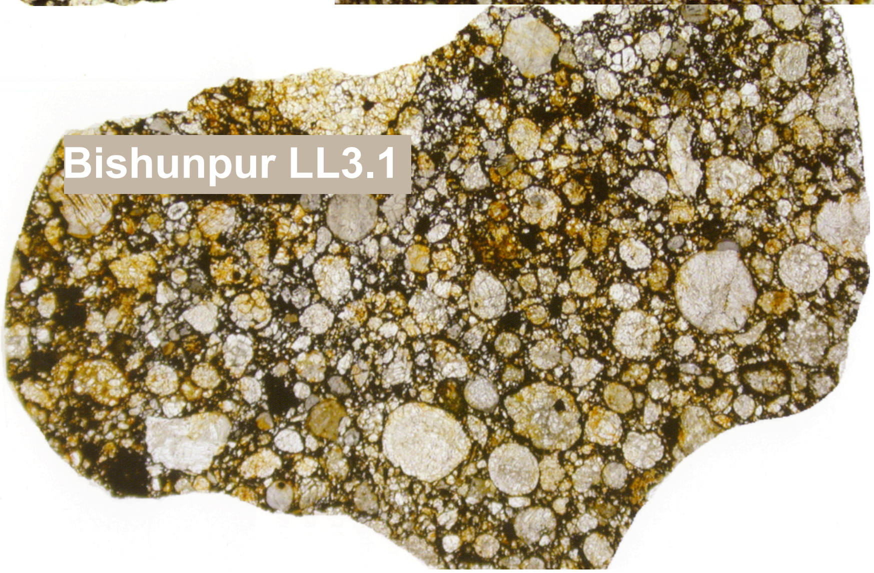
McKeegan et al 2008
GENESIS

3. Particle size & dust content

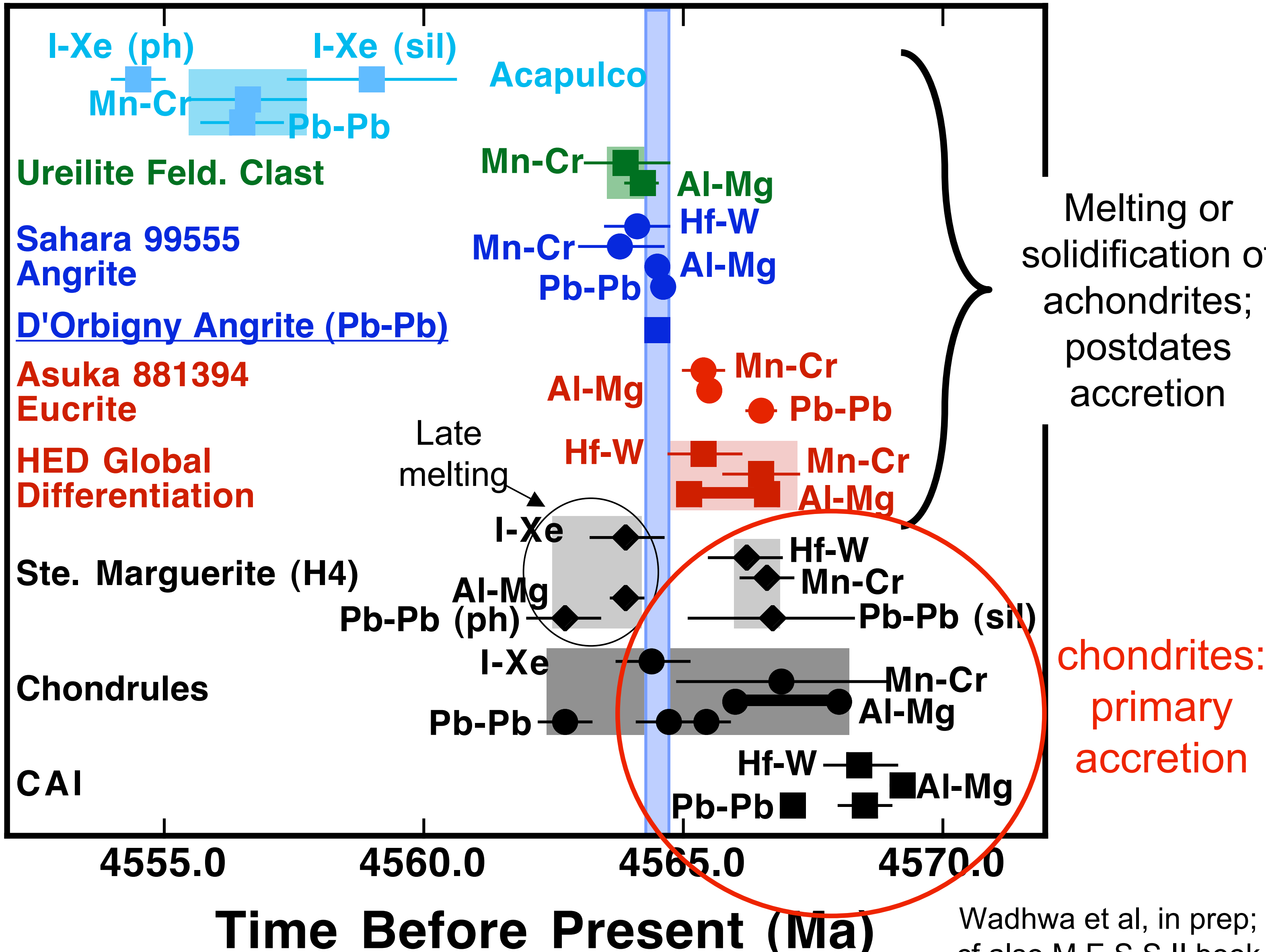








Short- and long-lived radiogenic isotopes for age dating



Wadhwa et al, in prep;
cf also M.E.S.S.II book

Few Myr age difference even between particles in the same rock!

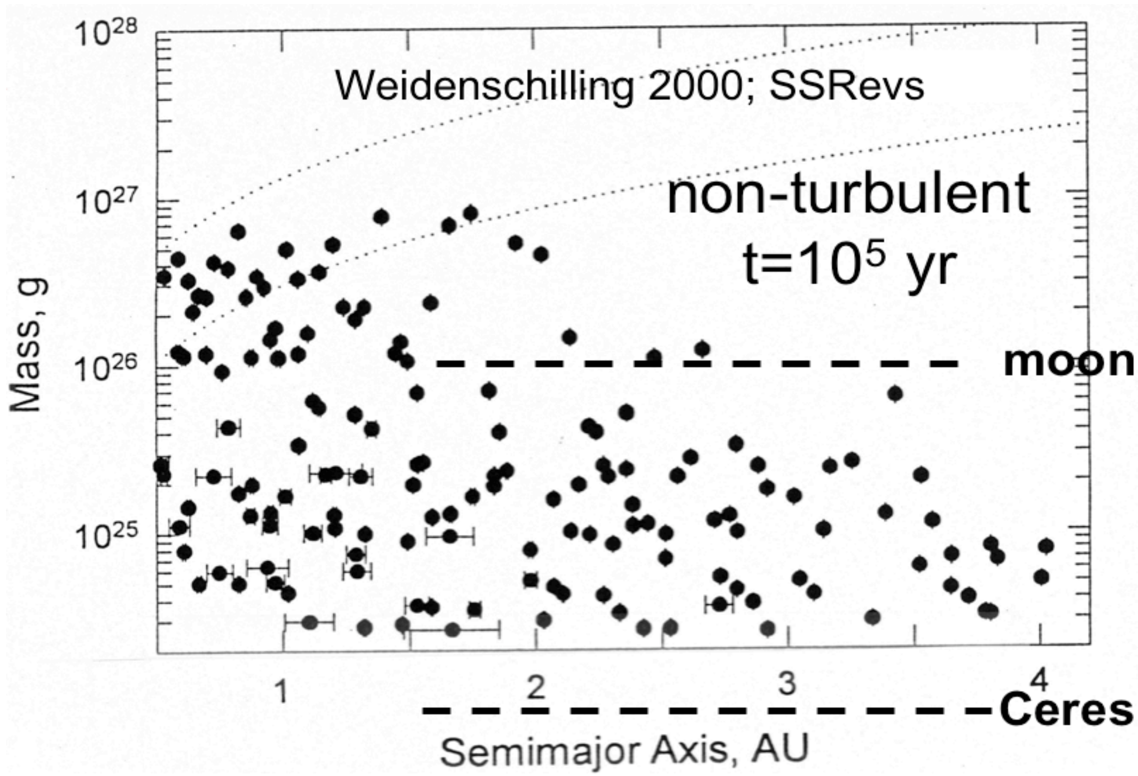
Primary Accretion was *INEFFICIENT*

Non-turbulent models lead to rapid growth in dense midplane

but isotopic age dating shows formation spanned several Myr

Anything >20km forming in first Myr melts from ^{26}Al decay

but melted asteroids are rare

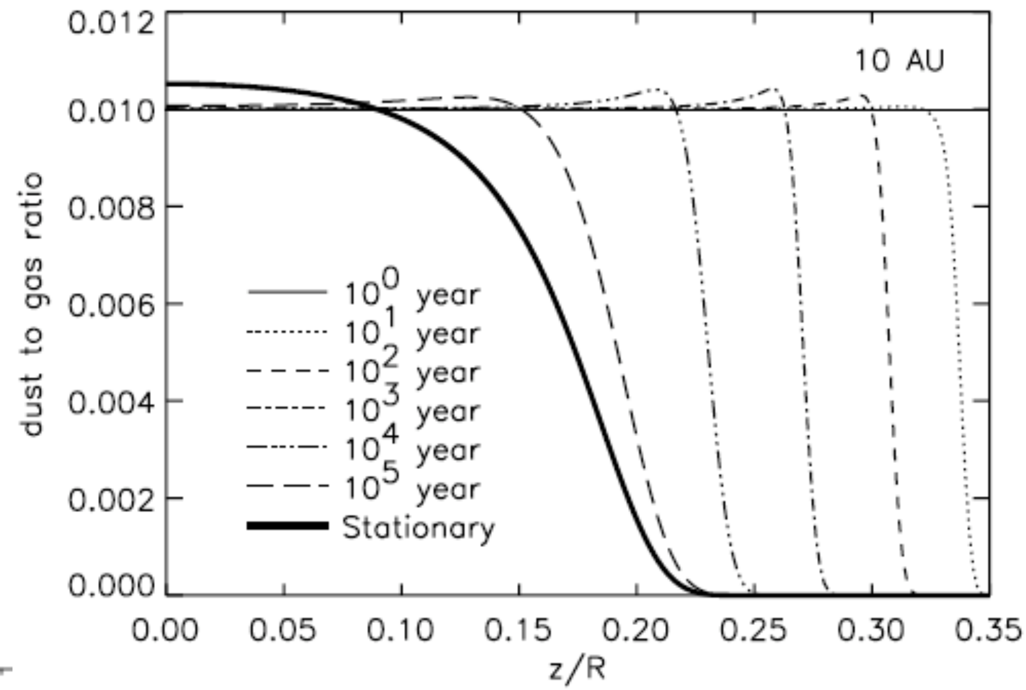


Turbulence can delay primary accretion

Few % of accretion energy from 10^{-8} M_{sun}/yr maintains $\alpha = 10^{-4}$ or so

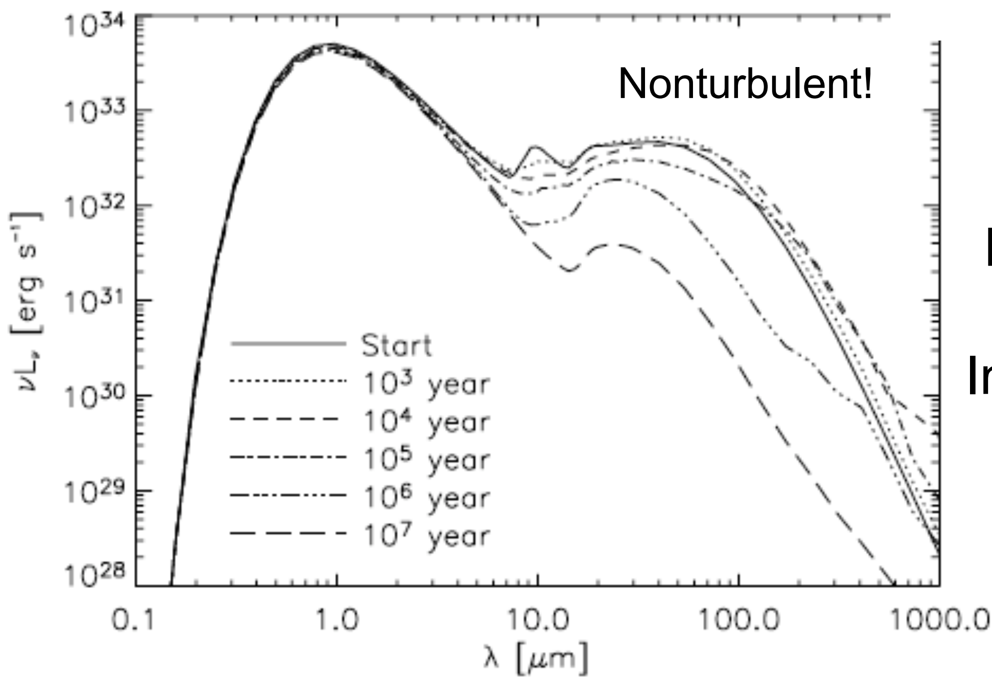
Some observations favor turbulence

Dullemond & Dominik 2004



Weak turbulence can maintain small grains at observed altitudes forever, in the absence of growth

Dullemond & Dominik 2005



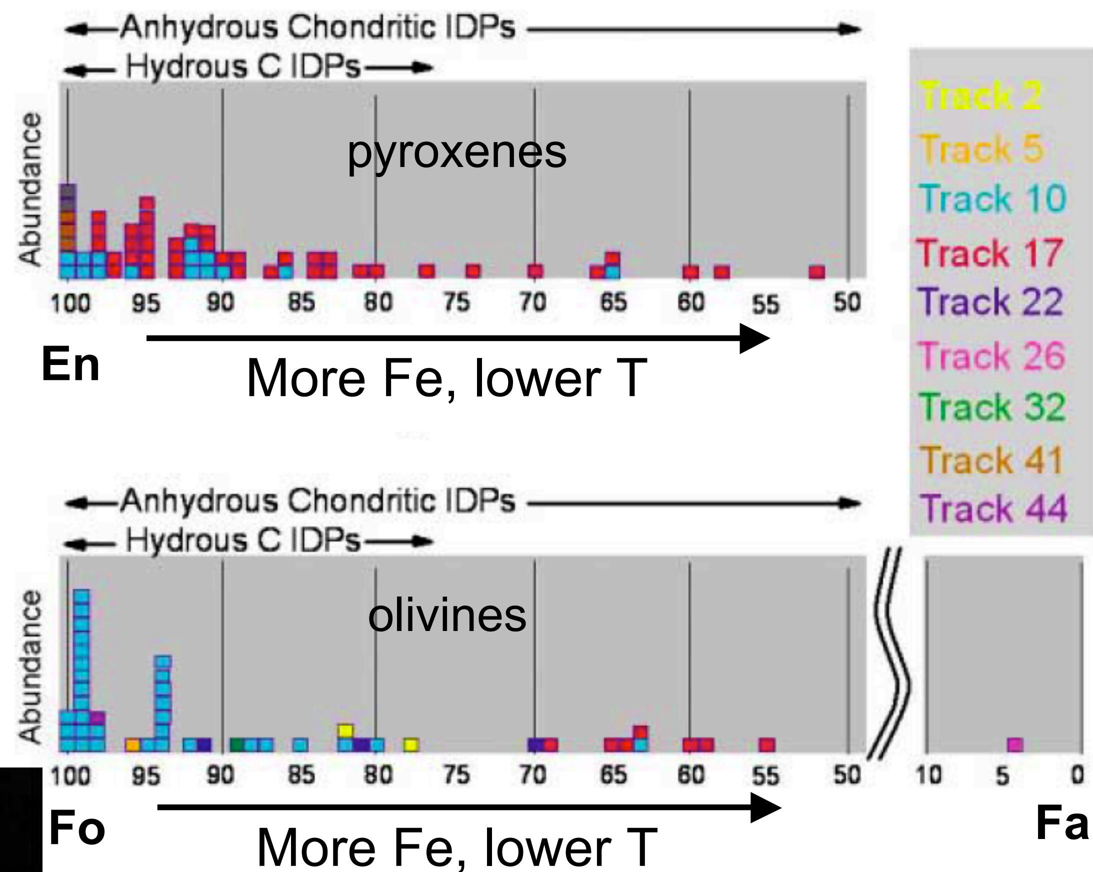
Low relative velocities ensure sticking; rapid growth leads to settling. Implies ongoing large-particle collisions AND turbulent transport of dust back to high altitudes

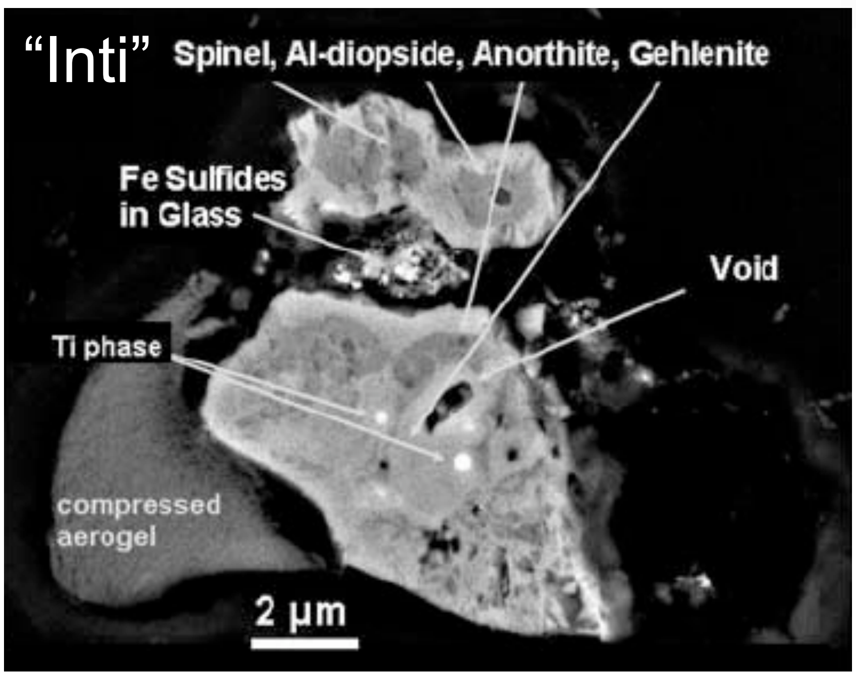
STARDUST:

nm-μm grains;
(CAI, Fe-Mg silicates);
crystallines abundant

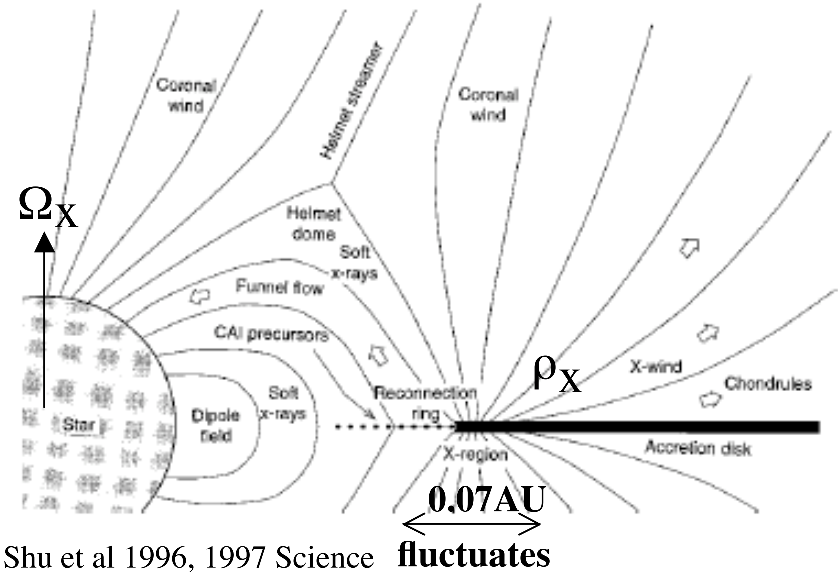
Zolensky et al Science 2006

Brownlee et al Science 2006

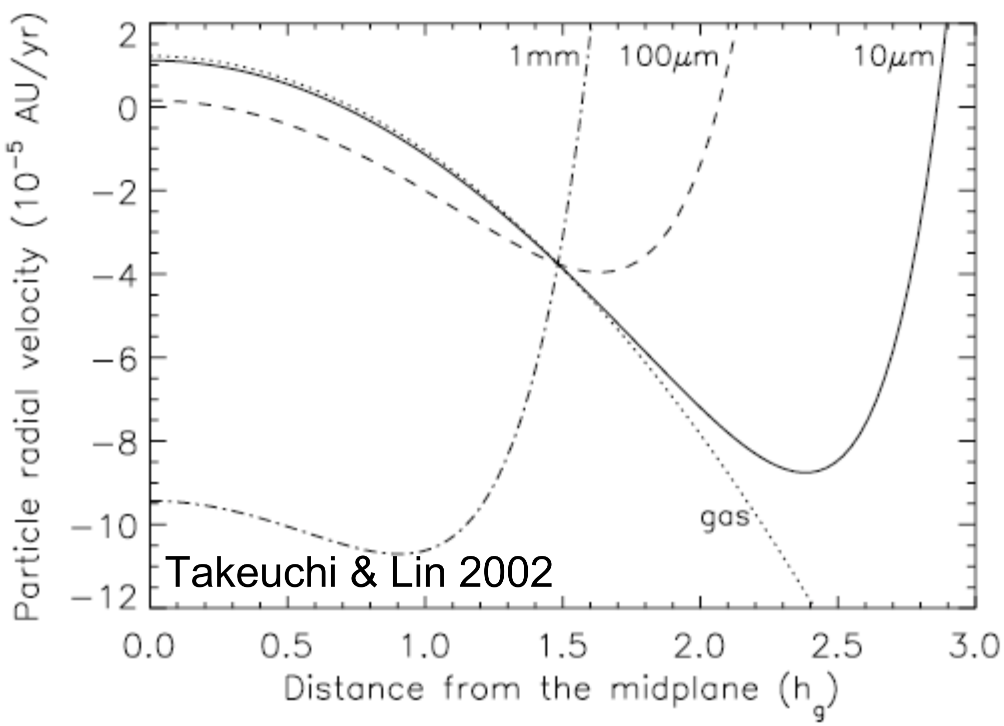


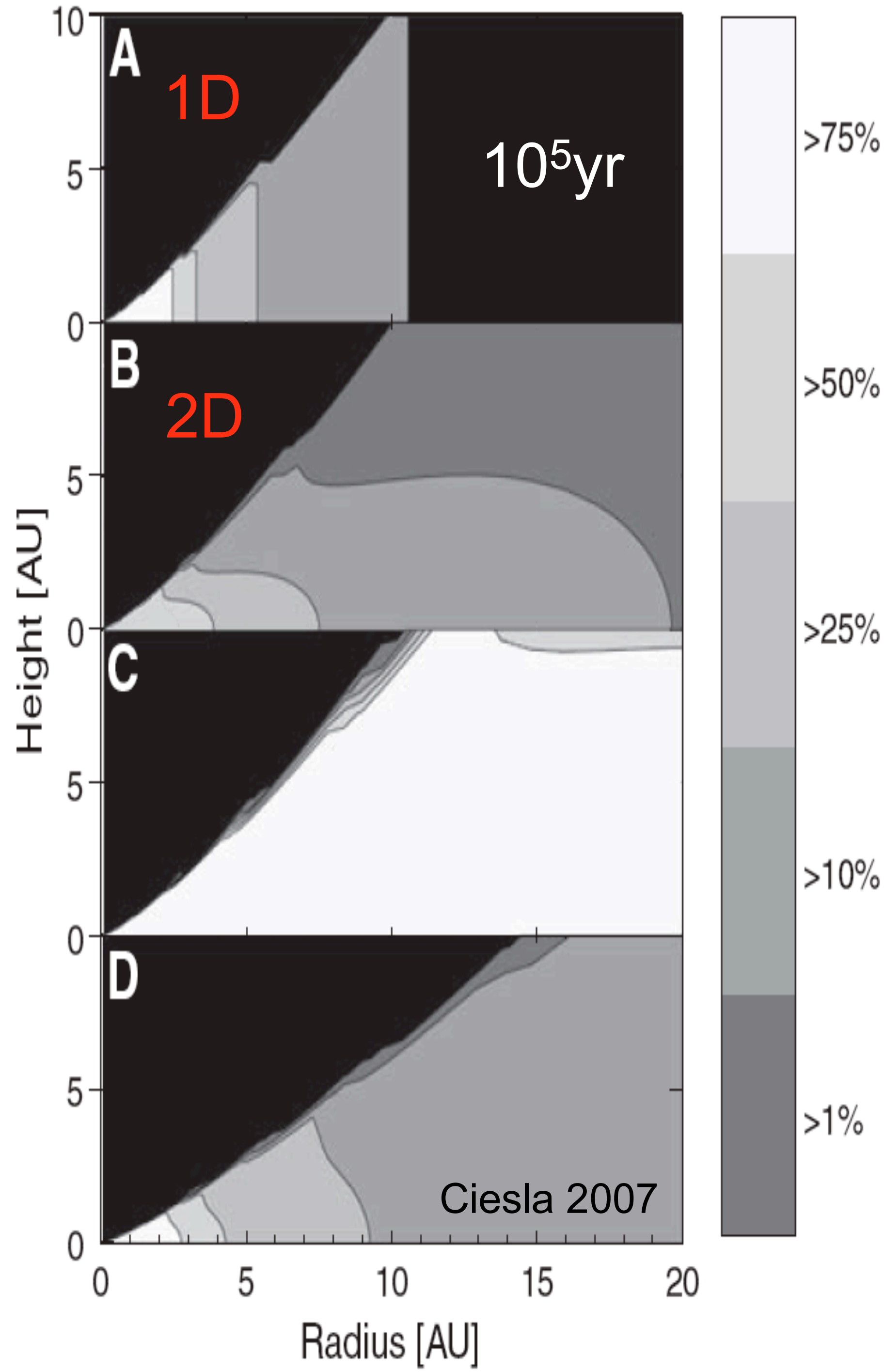


STARDUST team concludes:
Vigorous radial transport
from inner to outer nebula,
sampling a *wide variety*
of formation conditions

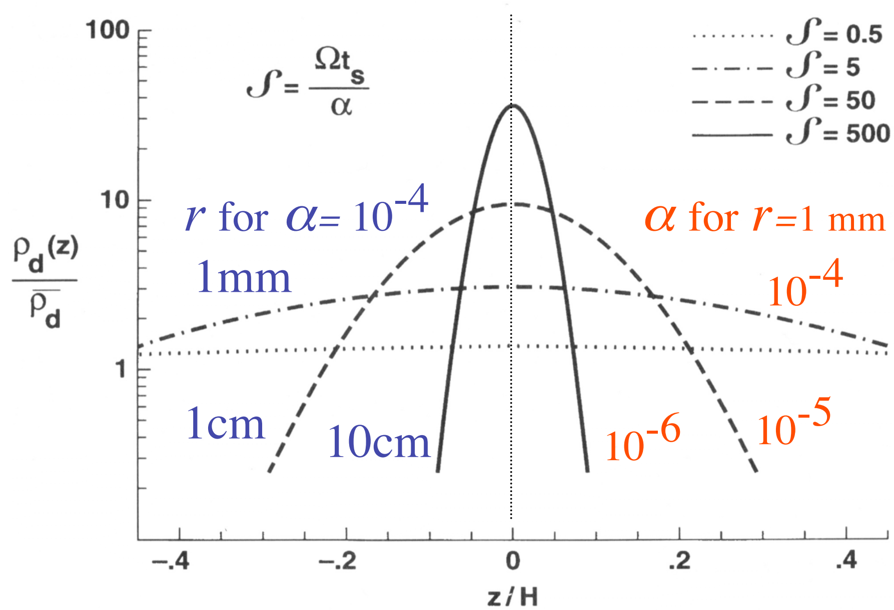


Shu et al 1996, 1997 Science
Liffman & Brown Icarus 1995





Turbulence keeps midplane densities low



Turbulence diffuses particles vertically, preventing "settling to the midplane" even after some growth has occurred

Adapted from Dubrulle et al 1995

Various *midplane instabilities* proposed over the years

(Safronov 1960, Goldreich & Ward 1973, Sekiya 1998 et seq;
Goodman & Pindor 1995; Youdin and Shu 2002 et seq;

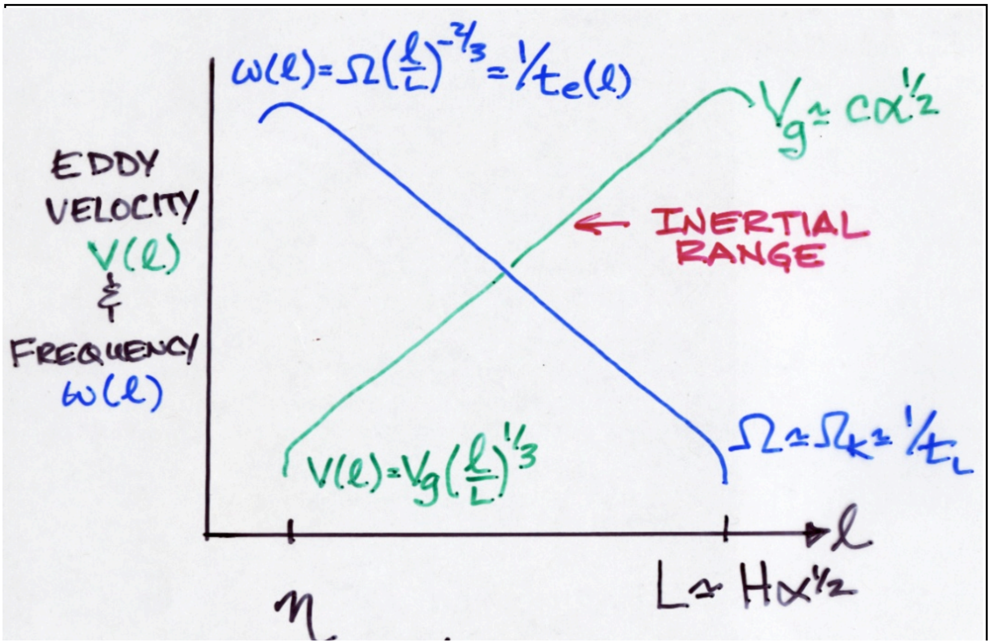
are precluded by global turbulence at levels $\alpha \ll 10^{-2}$

-and-

In nonturbulent nebulae, growth by sticking in dense midplane layers is already (too) rapid even without instabilities.

cf. reviews by Cuzzi & Weidenschilling, Met. Early Sol Syst II (2006); Dominik et al PPV (2007)

Gas turbulence drives particle velocities



Large eddies contain most of the energy, large eddy velocity $V_g \sim c\,\alpha^{1/2}$.

Large eddy frequency ~ the orbit freq;

Small eddies have faster overturn times

Particle relative velocities can be calculated for any turbulent intensity

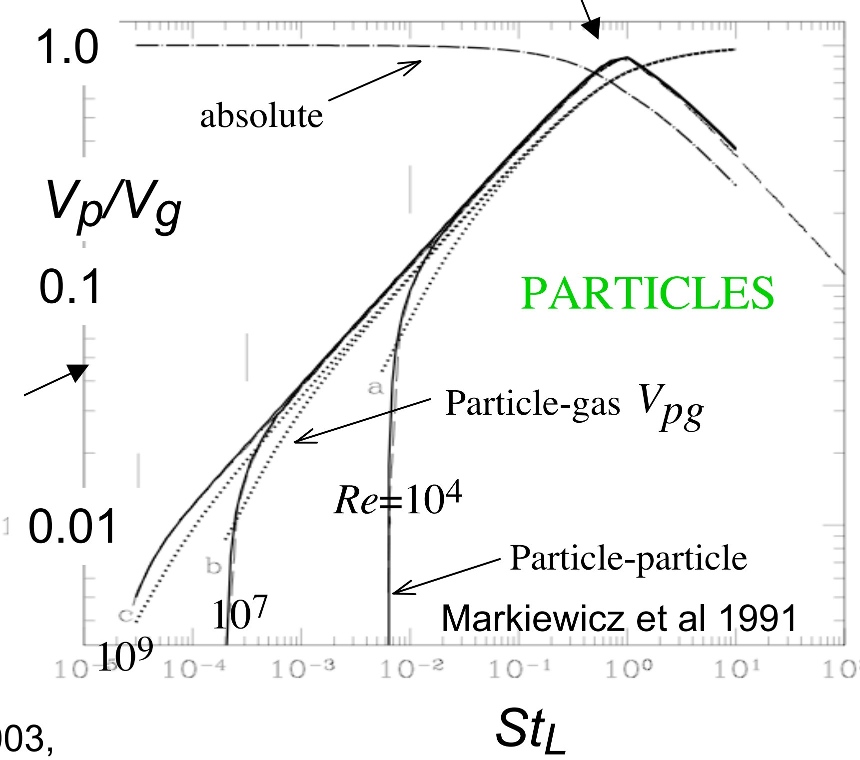
Particle stopping time

$$t_s = r\,\rho_s / c\,\rho_g$$

(expr. changes for r > gas mfp)

Peak velocities for particles with t_s comparable to large eddy time

$(St_L = t_s\,\Omega_L = 1)$



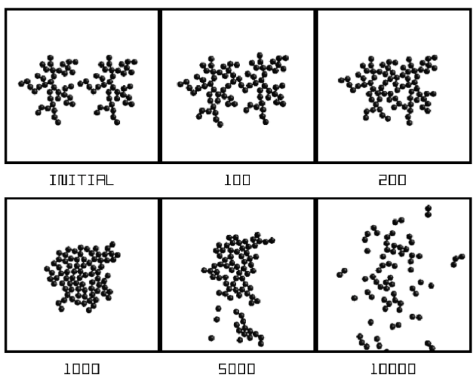
Völk et al 1980, Markiewicz et al 1991, Cuzzi and Hogan 2003, Ormel and Cuzzi 2007, Youdin and Lithwick 2007, Carballido et al 2006,2008

Sticky business

Critical "sticking" velocity varies with material and monomer size

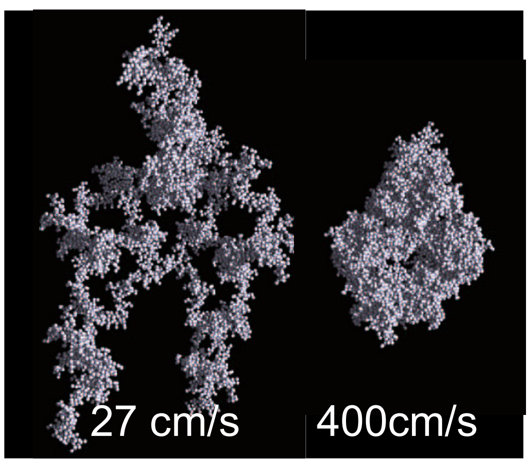
(J. Blum, this mtg)

Sticking is fairly robust, up to (deci?)meter-size



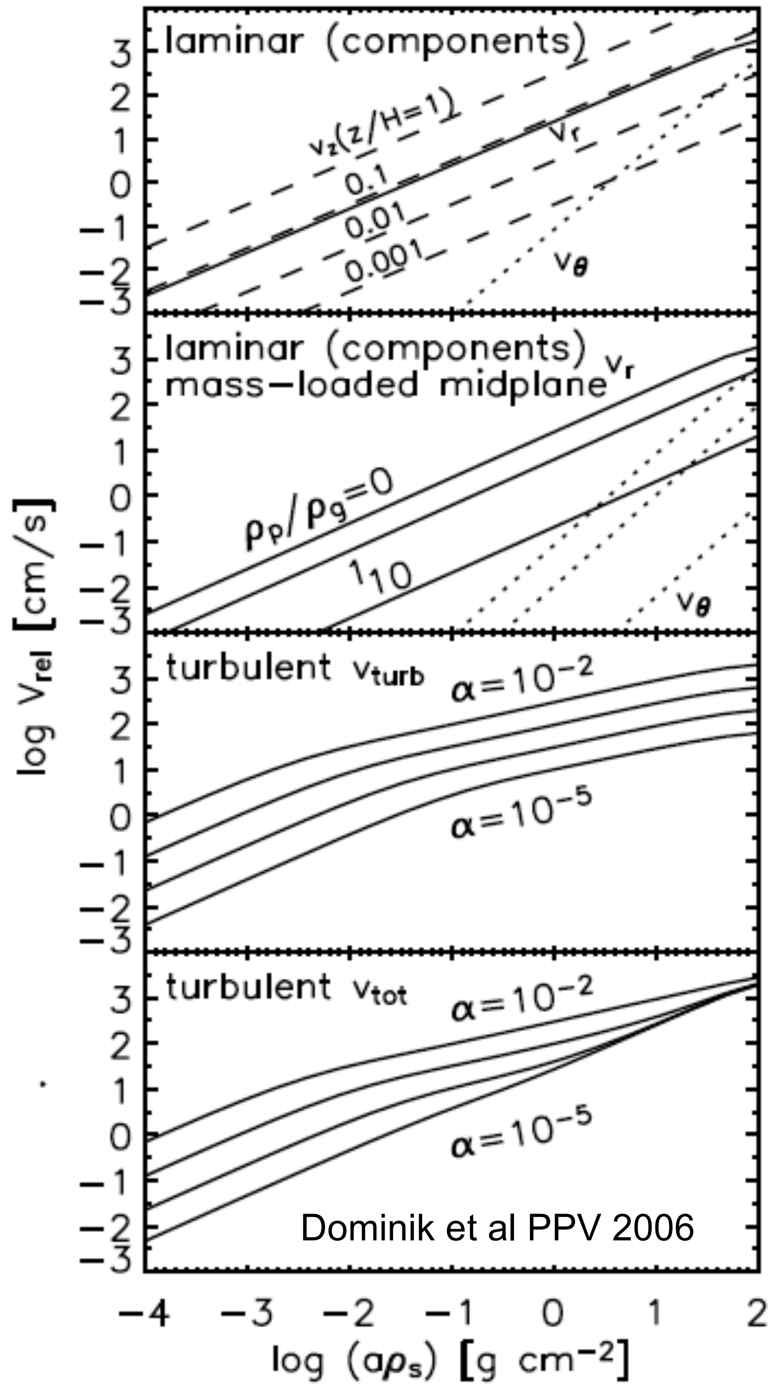
Dominik & Tielens 1997

2D; 3 regimes depending on critical energies E_{roll}, E_{stick}

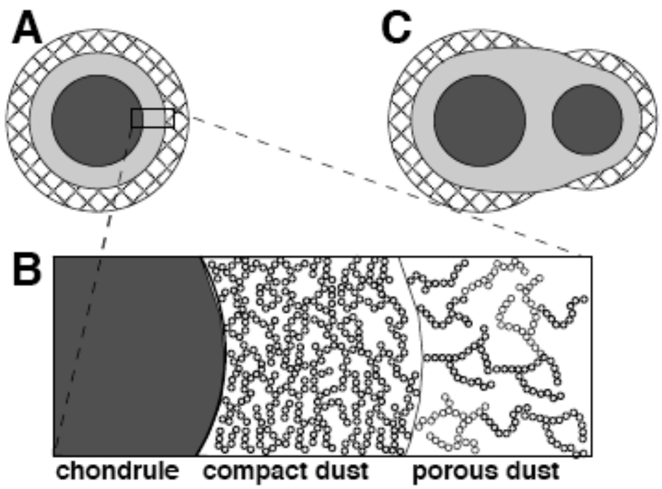


Suyama et al 2008, Wada et al 2008 (LPSC)

3D; compaction & sticking up to 4m/s (high for aggregates, maybe relevant for chondrule rims)

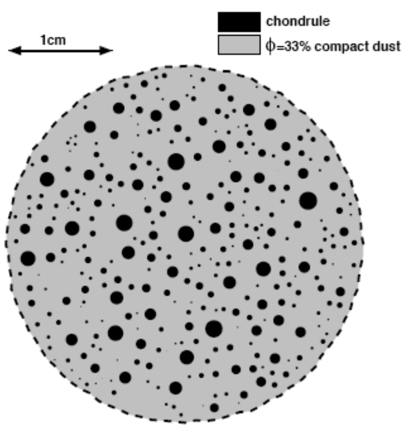


Small particle growth theory (Dominik & Tielens 97, Ormel et al 2008 ApJ in press)

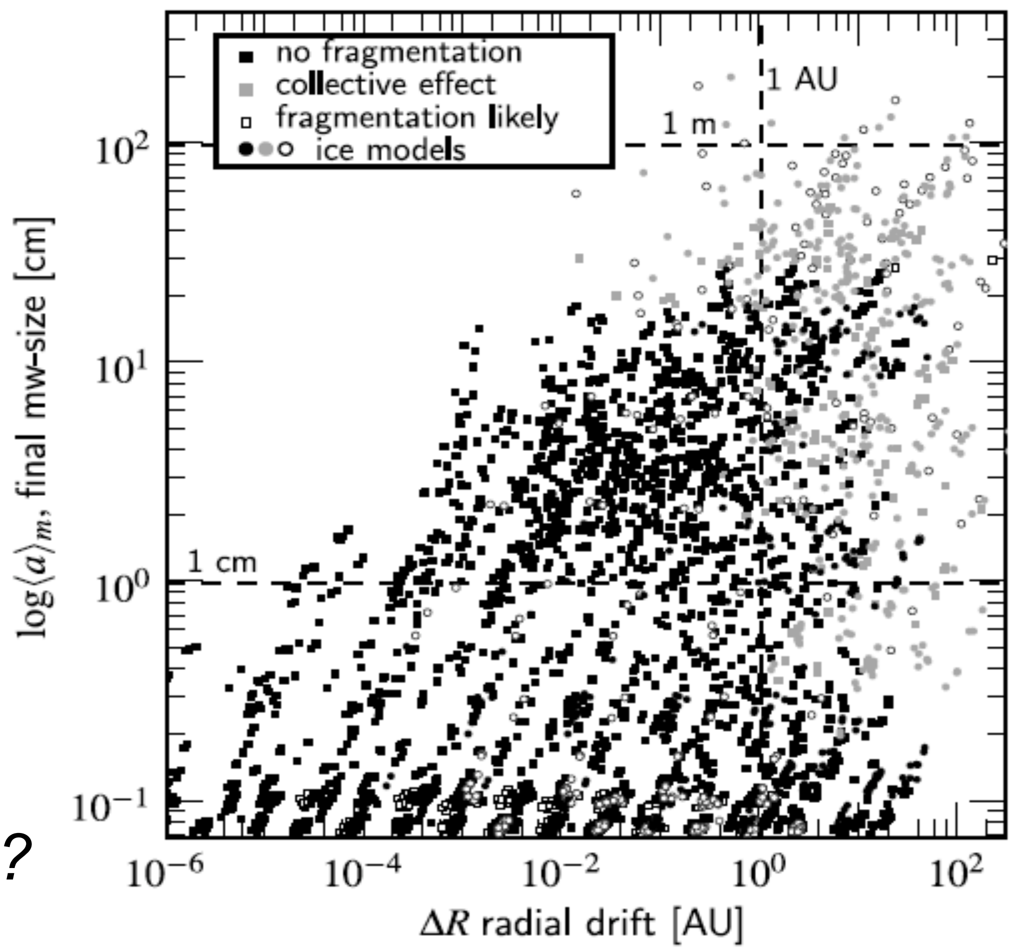


$$E_{\rm stick} = A_{\rm stick}\frac{\gamma^{5/3}a_\mu^{4/3}}{\mathcal{E}^{2/3}}$$

$$E_{\rm roll} = 6\pi^2\xi_{\rm crit}a_\mu\gamma = A_{\rm roll}\xi_{\rm crit}a_\mu$$



Average porosity ~ 40%



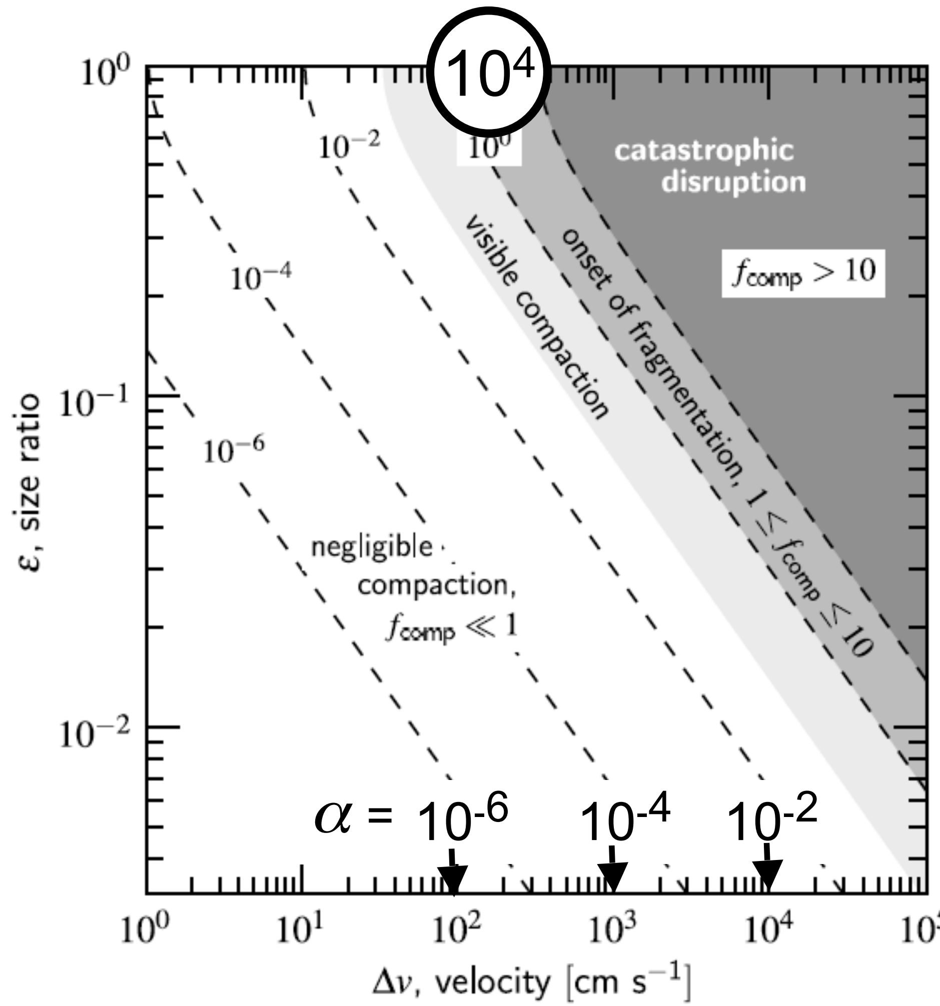
$E_{coll} > N\, E_{roll}$ -> *bounce*

$E_{coll} > 10\, N\, E_{stick}$-> *fragment?*

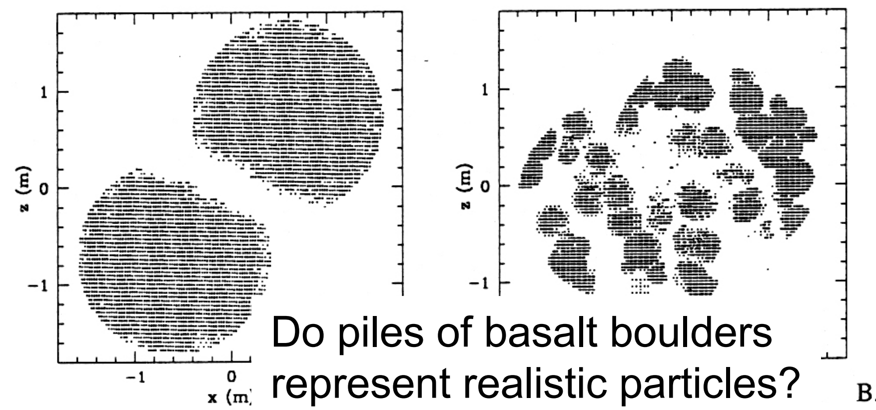
What are the disruption strengths of m-size particles?

$Q^* \sim v^2$ for $m_1 \sim m_2$

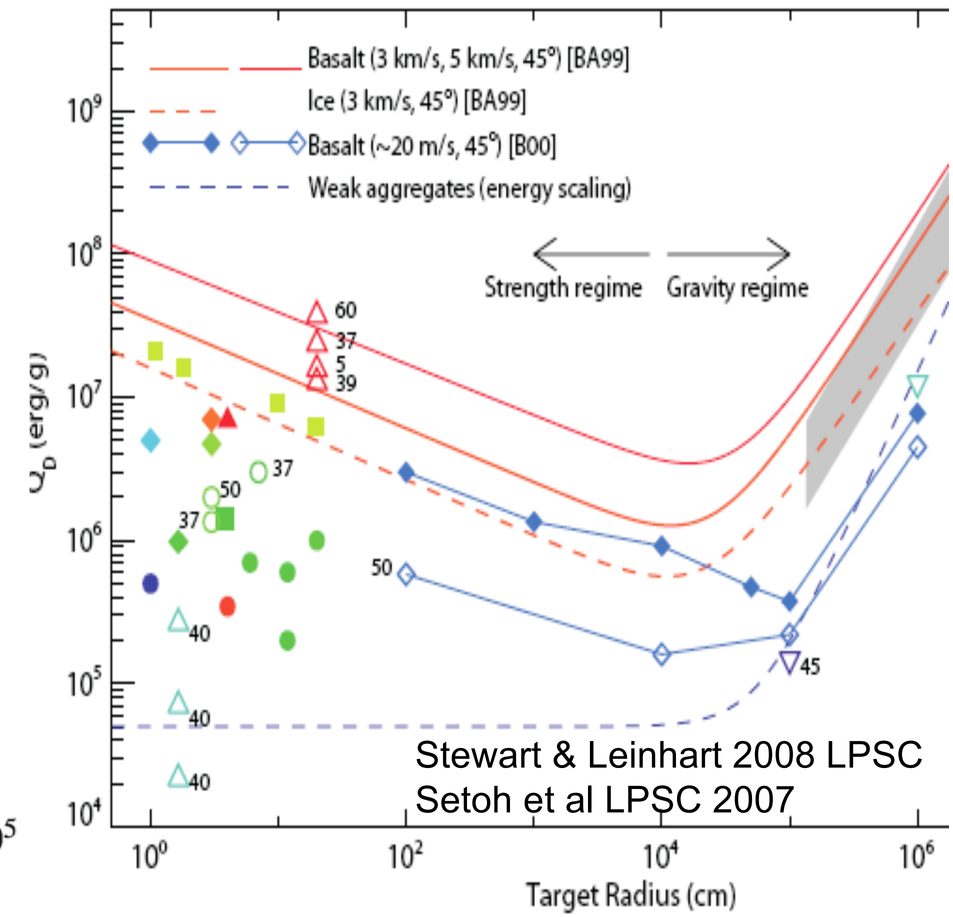
Ormel et al (2008) ApJ in press



Benz 2000 Sp Sci Revs



Do piles of basalt boulders represent realistic particles?



Stewart & Leinhart 2008 LPSC

Setoh et al LPSC 2007

SPH simulations (Sirono 2004 Icarus)

V = 10m/s
normalized compressive and tensile strengths (Σo, To) ~ 10^{-2}, 10^{-3} of solid, or (8000, 70000) dyn/cm^2

Projectile here is much smaller than target; equal mass would provide 30x larger energy, suggesting 5-6 x smaller V_{crit}; again ~ 1-2 m/s

Conditions for collisional growth of a grain aggregate 443

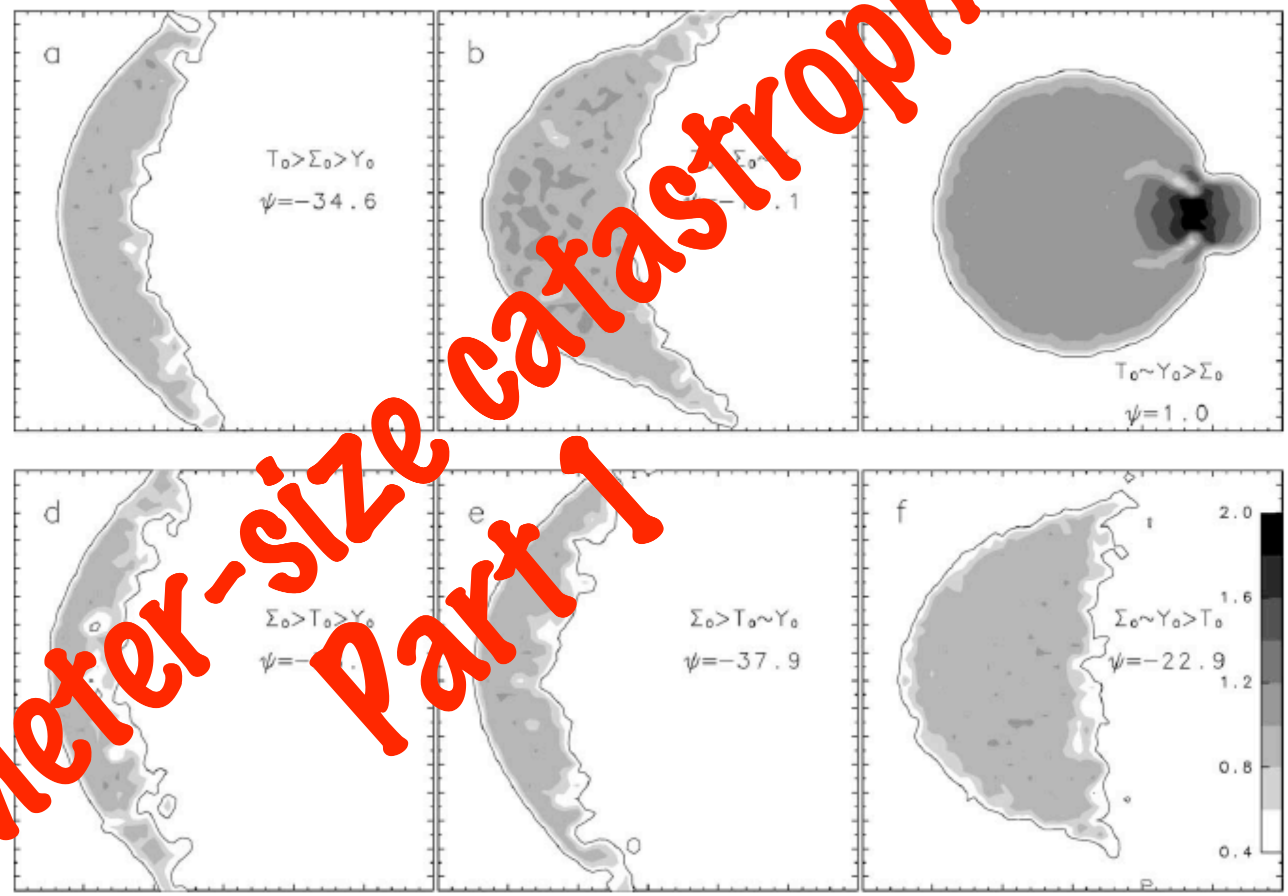


Fig. 13. Results of collisions having various orders of compressive, tensile, and shear strengths. Sticking takes place only if the compressive strength is the lowest among the three components (panel c).

The meter-size catastrophe, Part 1

And, Langkowski et al 2007 find (Σo, To) ~ 2000-10000 dyn/cm^2

Collisions may preclude growth past around meter-size

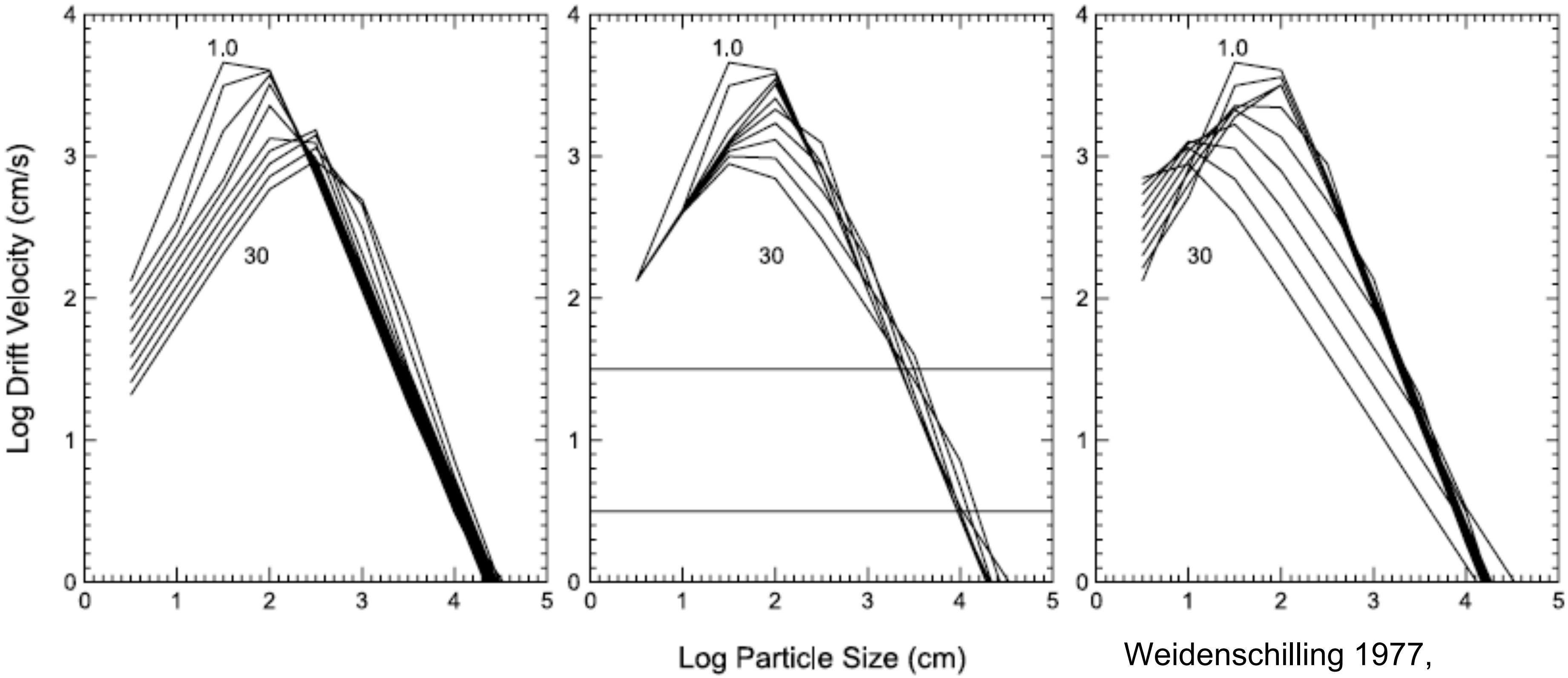
Transport of solids by inward radial drift (gas drag)

On average, $dP/dr = -\beta R\Omega^2$ *near midplane*

Gas orbits slower than keplerian, so particles incur headwind and lose angular momentum

Peak radial drift speed $V_D = \beta V_K$ ~ 1 AU/century

Reduced in dense midplane layers (if non-turbulent)

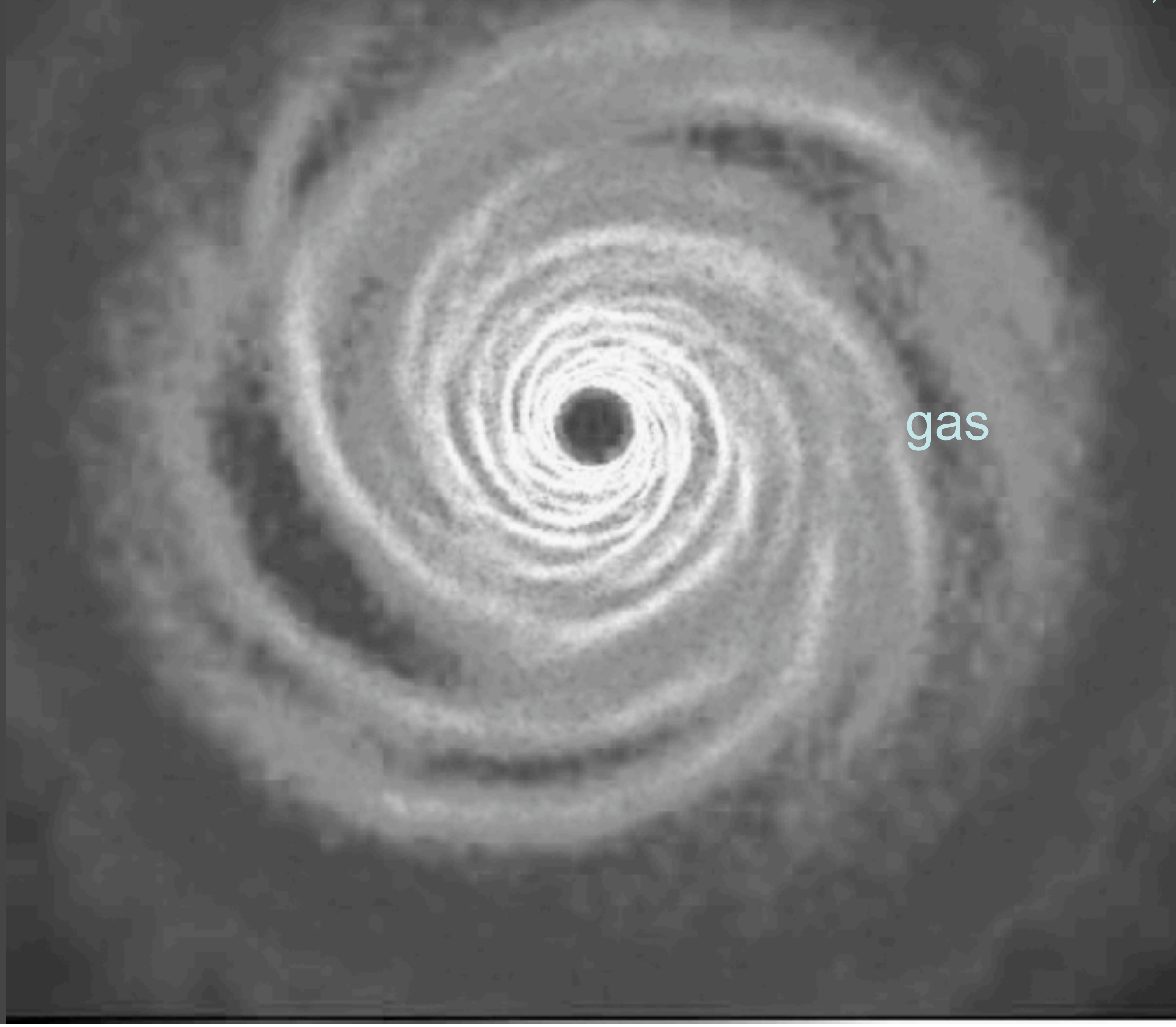


Weidenschilling 1977,
Cuzzi & Weidenschilling 2006

Particles accumulate in radial pressure maxima

Haghigipour and Boss 2003a,b; Rice et al 2004

also Johansen et al 2006, 2007



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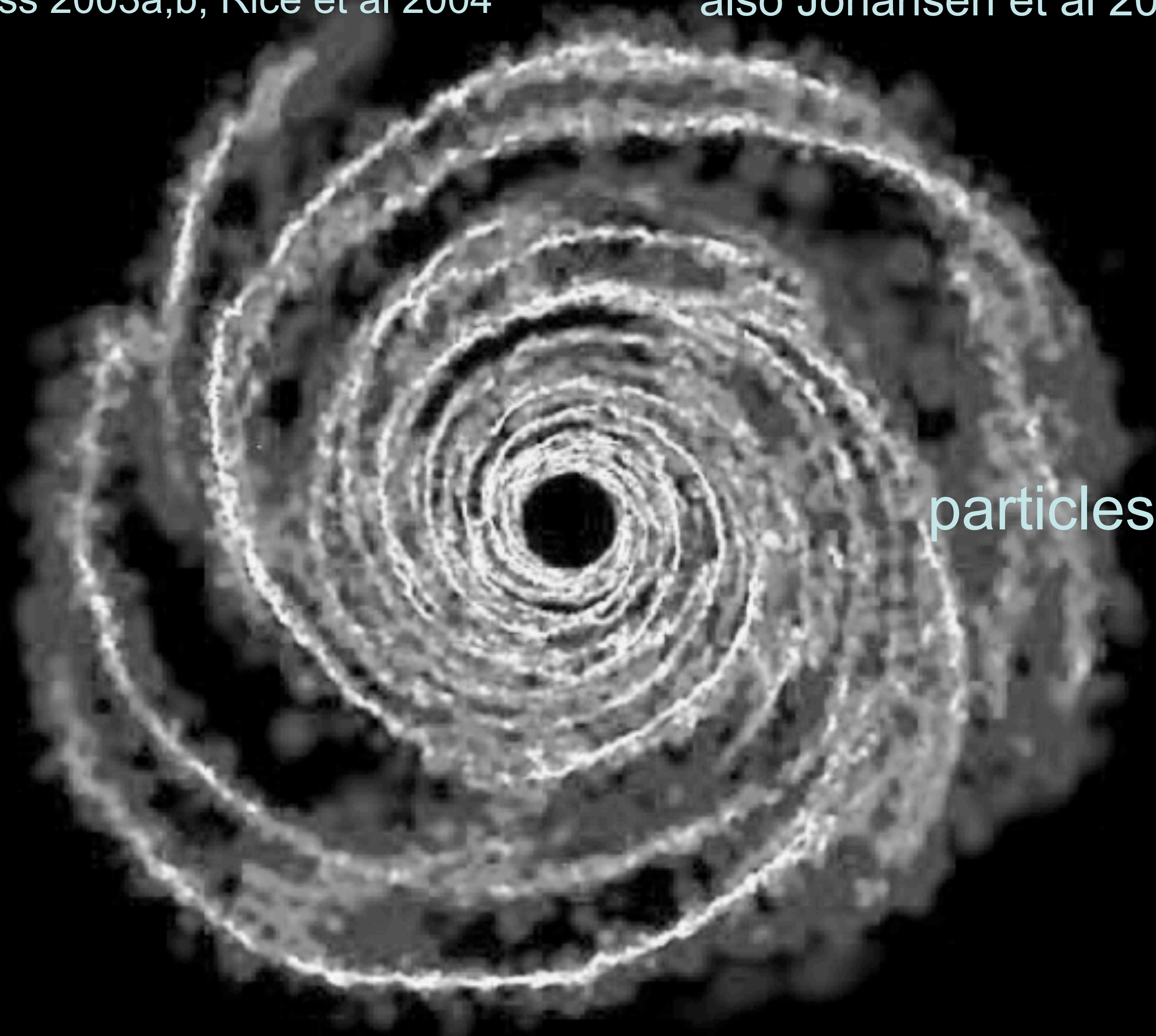


But - effect only reduces radial drift by half or so (Johansen et al 2006)

“Radial drift barrier”

The meter-size catastrophe, Part 2

Particle has to be able to grow before leaving its environment

$$t_{res} = a/\dot{a} > r/\dot{r} = t_{gro}$$

$$\dot{a} = \beta V_K (r/1\mathrm{m}) = \beta a \Omega (r/1\mathrm{m}), \text{ where } \beta \sim 10^{-3}$$

$$\dot{r} = \dot{m}/(4\pi r^2 \rho_s) = \Delta V \rho_{loc}/\rho_p, \text{ where } \Delta V \sim \text{few m/s}$$

$$(r/1\mathrm{m})^2 < \Delta V(\mathrm{m/s})(\rho_{loc}/\rho_p)/\beta\Omega$$

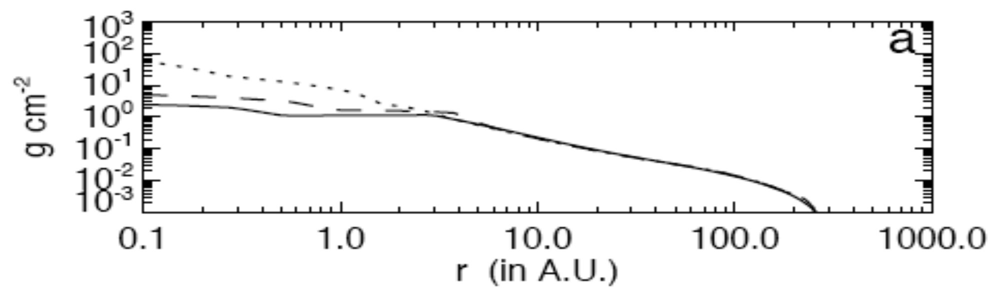
$$\text{suppose } \rho_{loc} \sim 0.1\rho_{gas}; \text{ then } r \sim 1\mathrm{m}$$

Brauer, Dullemond, Henning A&A in press

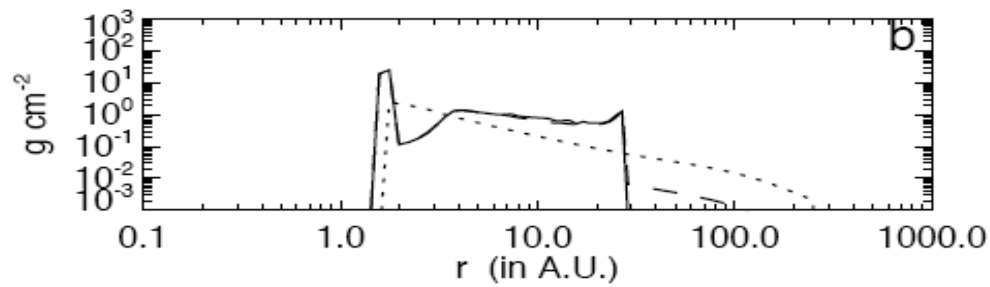
Radial drift

Drift into the sun?

Significant mass transport may invalidate concept of "minimum mass nebula"



Stepinski and Valageas 1996, 1997

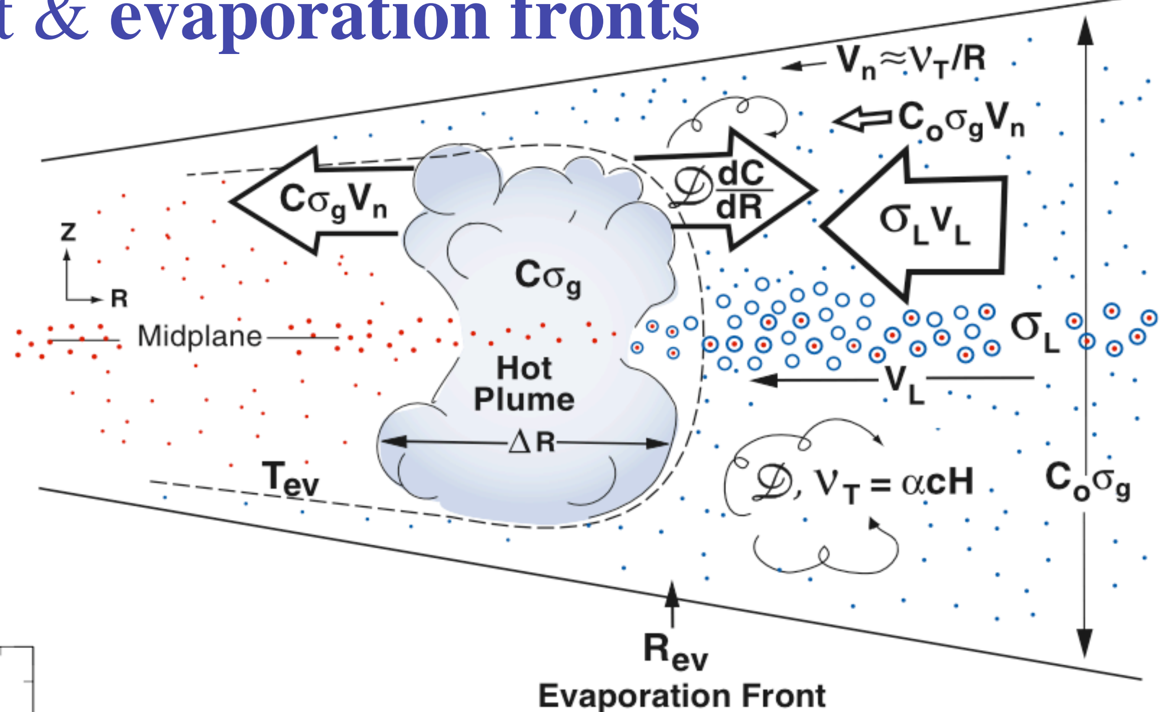


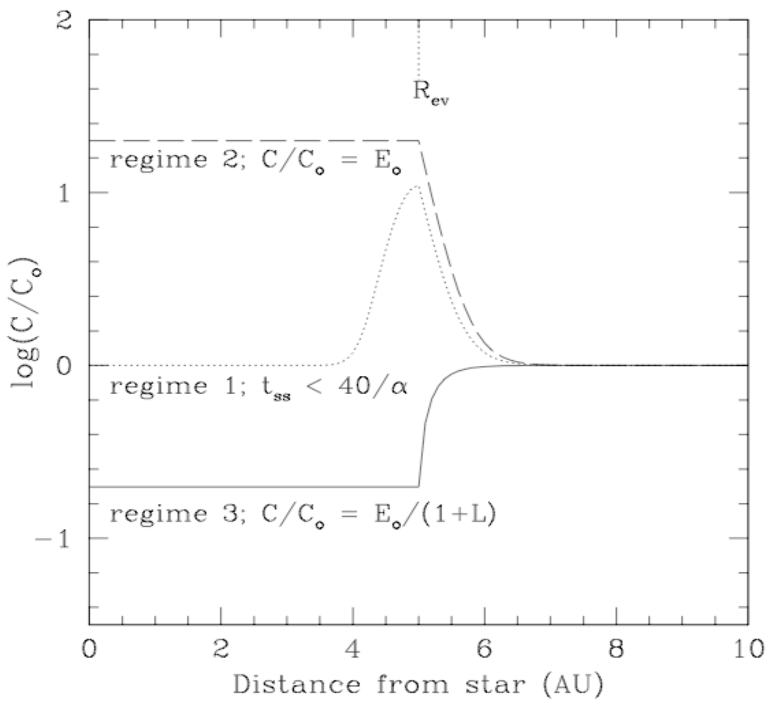
Radial drift & **evaporation fronts**

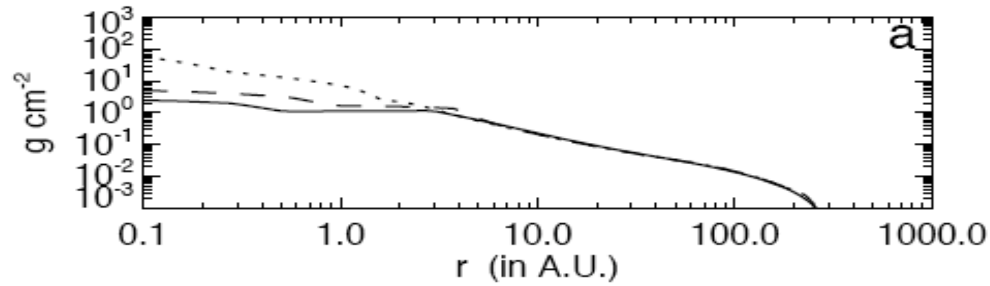
~~Drift into the sun?~~

Cyr et al 1998, Supulver & Lin 2000
Cuzzi & Zahnle 2004 ApJ
Cuzzi et al 2003 Icarus

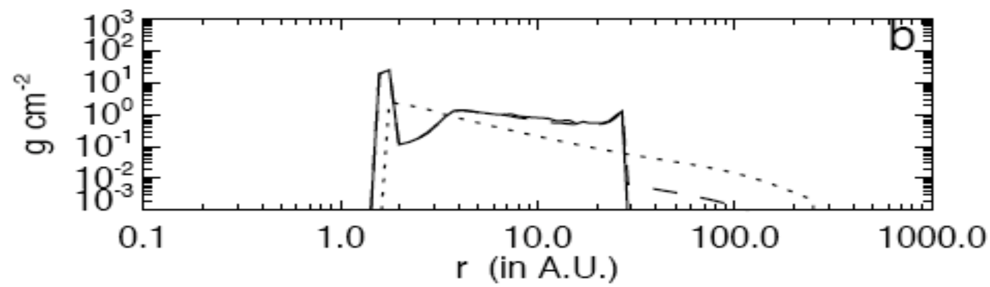
$$E \approx \frac{f_L V_L}{V_n} \approx \frac{f_L}{\alpha}$$







Stepinski and Valageas 1996, 1997

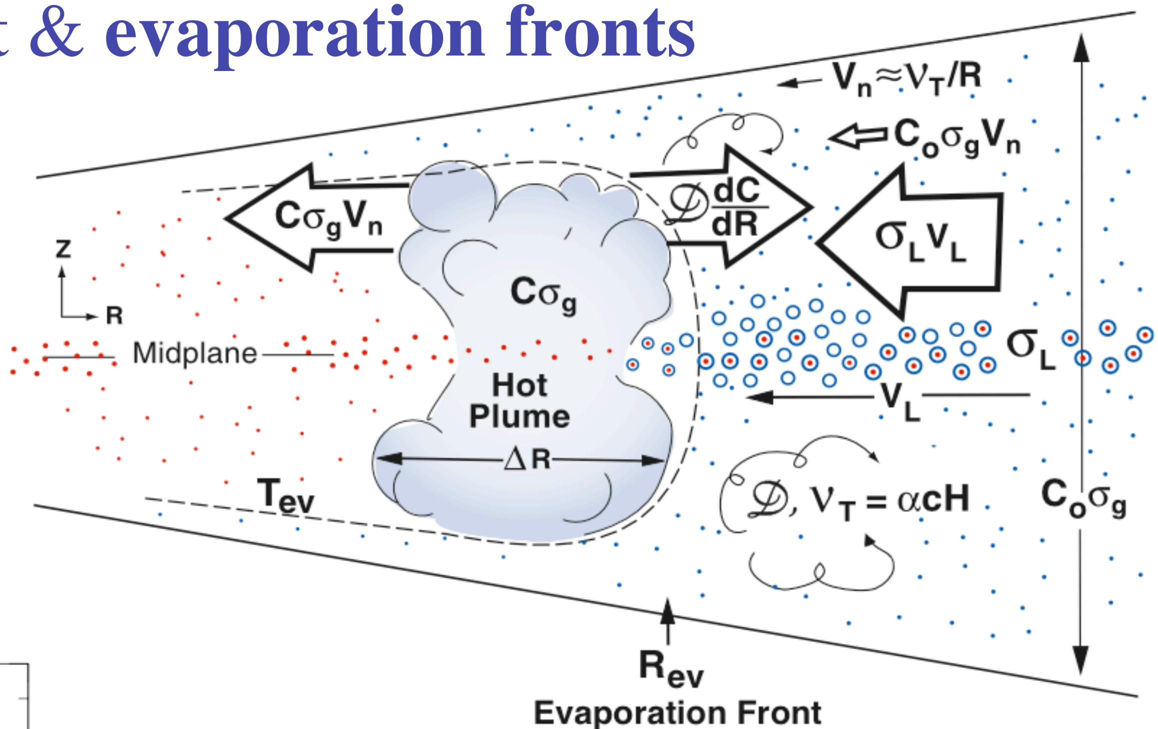


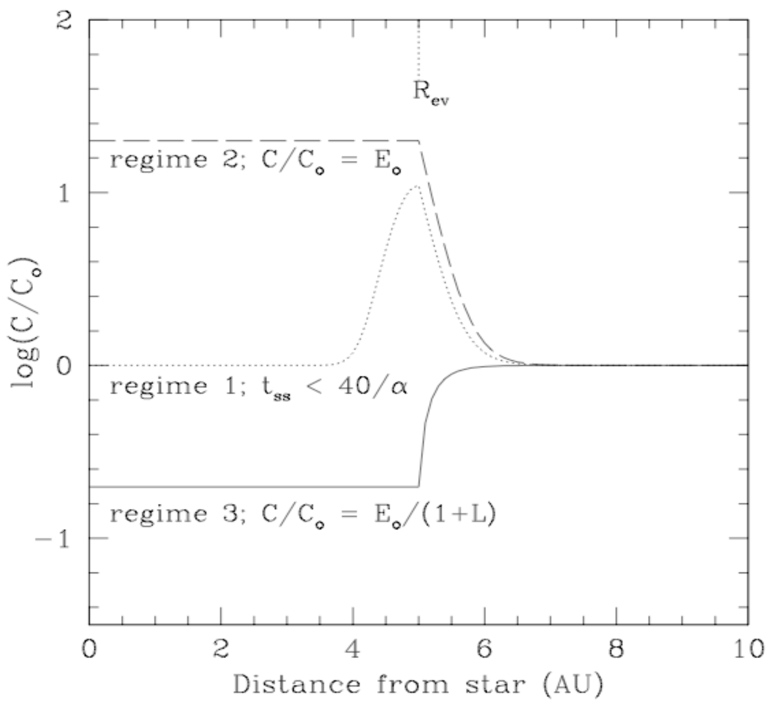
Radial drift & **evaporation fronts**

Drift into the sun?

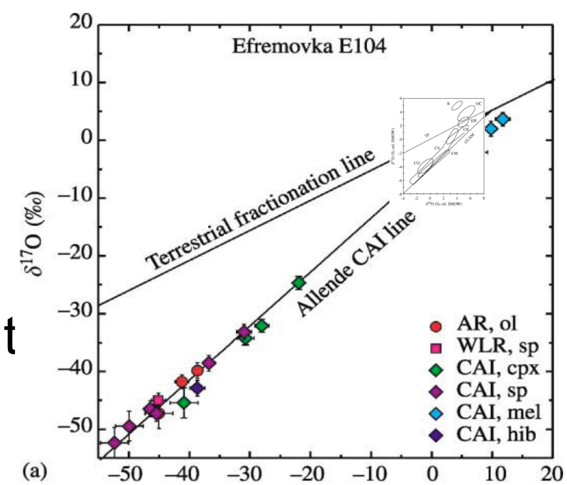
Cyr et al 1998, Supulver & Lin 2000
Cuzzi & Zahnle 2004 ApJ
Cuzzi et al 2003 Icarus

$$E \approx \frac{f_L V_L}{V_n} \approx \frac{f_L}{\alpha}$$





Water carries high $^{17,18}O$ signal; radial transport leads to variable oxygen abundance and isotopic content



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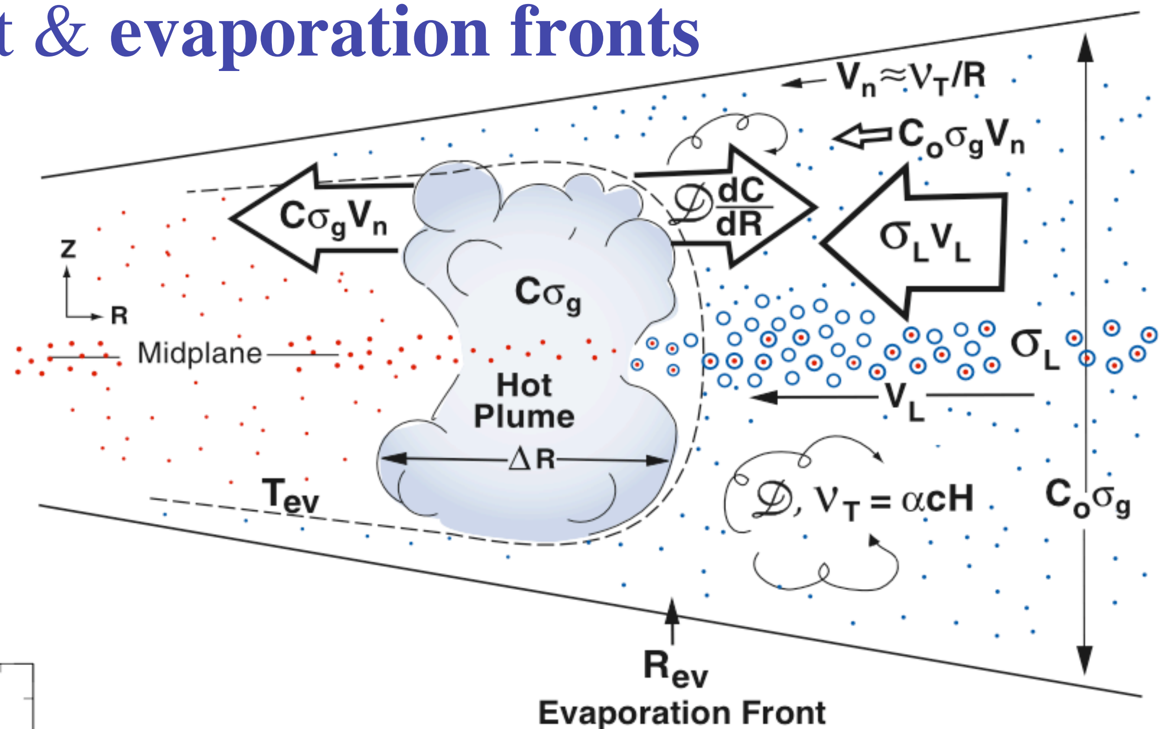
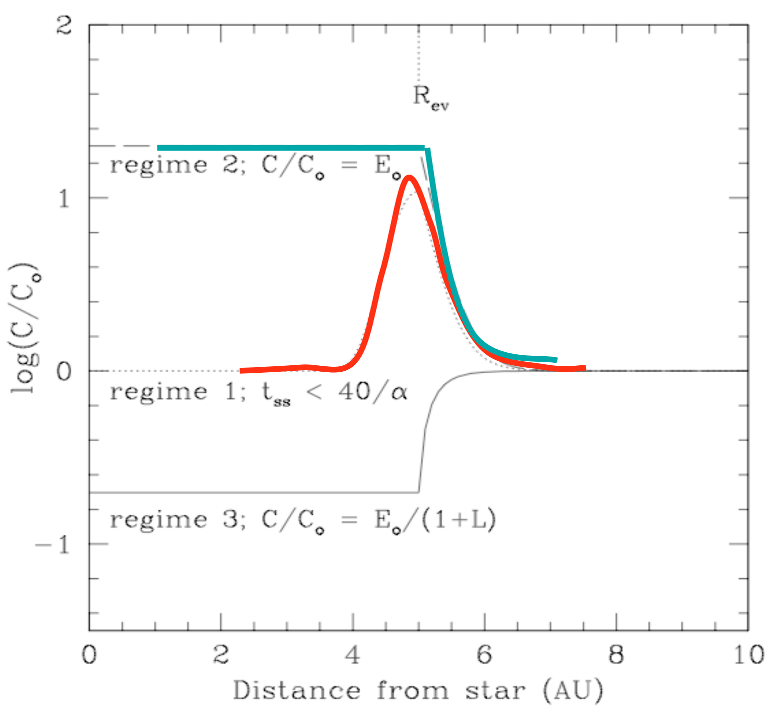
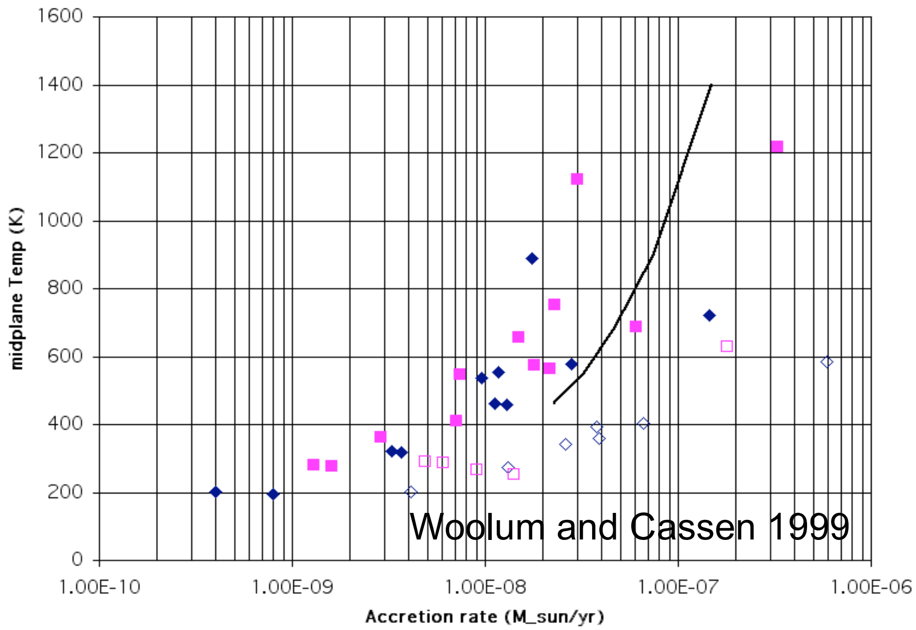


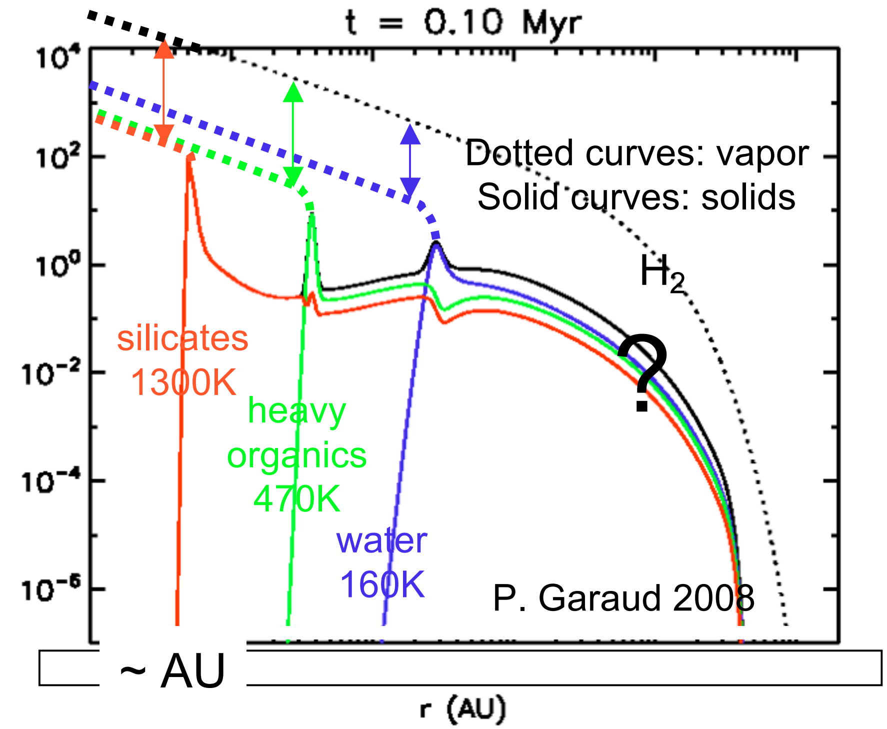


Future high resolution interferometric or spectroscopic studies might resolve EF structure; is it a ring or a disk?

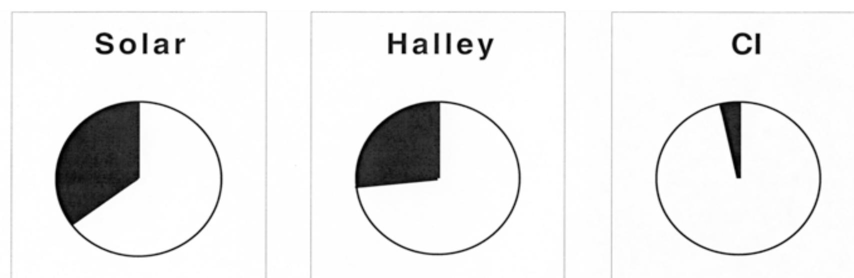
Silicate/Carbon/etc EF's?

Early inner solar system: silicate EF?





Drifting primordial rubble
is carbon-rich; refractory C/O
in Halley is 40-50x chondritic

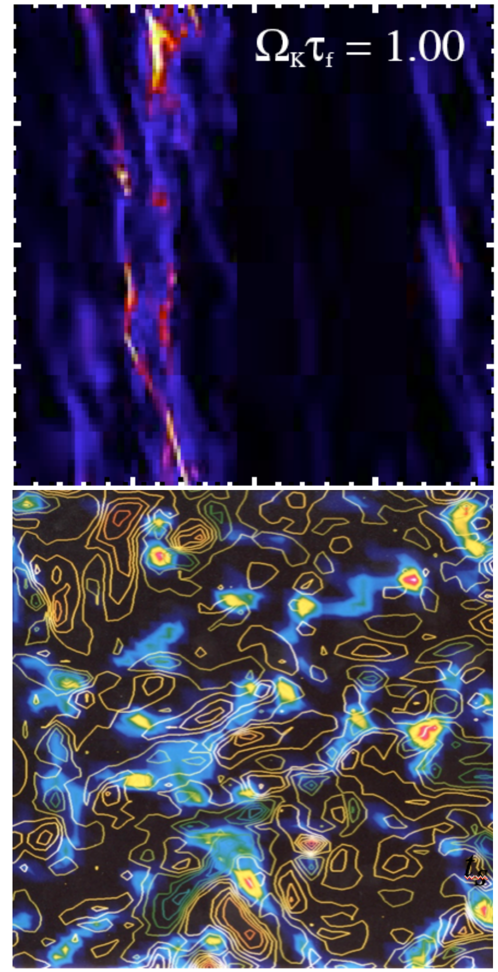


Production of CO/CO_2 in *earliest*, hot inner nebula as evaporating silicates oxidize refractory carbon? Possibly decorrelated from H_2O abundance?
(Najita et al, Carr et al, Eisner et al, Salyk et al, others)

Presently two scenarios for planetesimal accretion in turbulence giving inefficient accretion :

Three-stage instability
in *meter-size* particles
triggered by pressure ridges
around large-scale eddies,
fostered by streaming instability,
and completed by GI
(Johansen et al 2007)

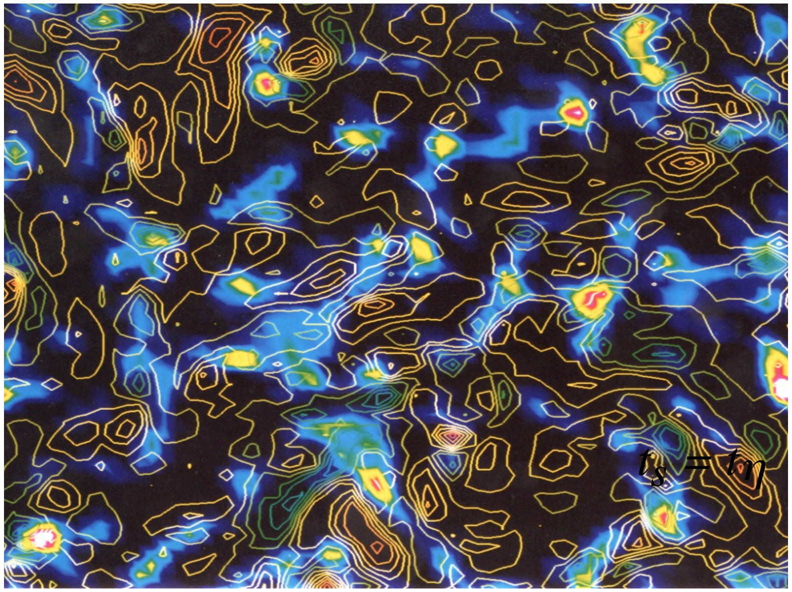
Two-stage instability
in *mm-size* particles
triggered by aerodynamic
intermittency and completed
by slow sedimentation
under self-gravity
(Cuzzi et al various)

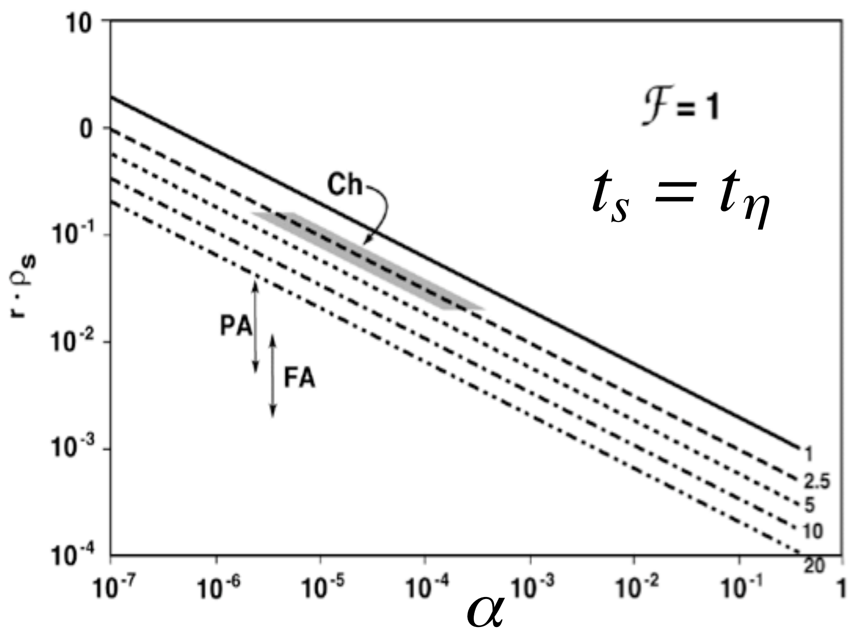


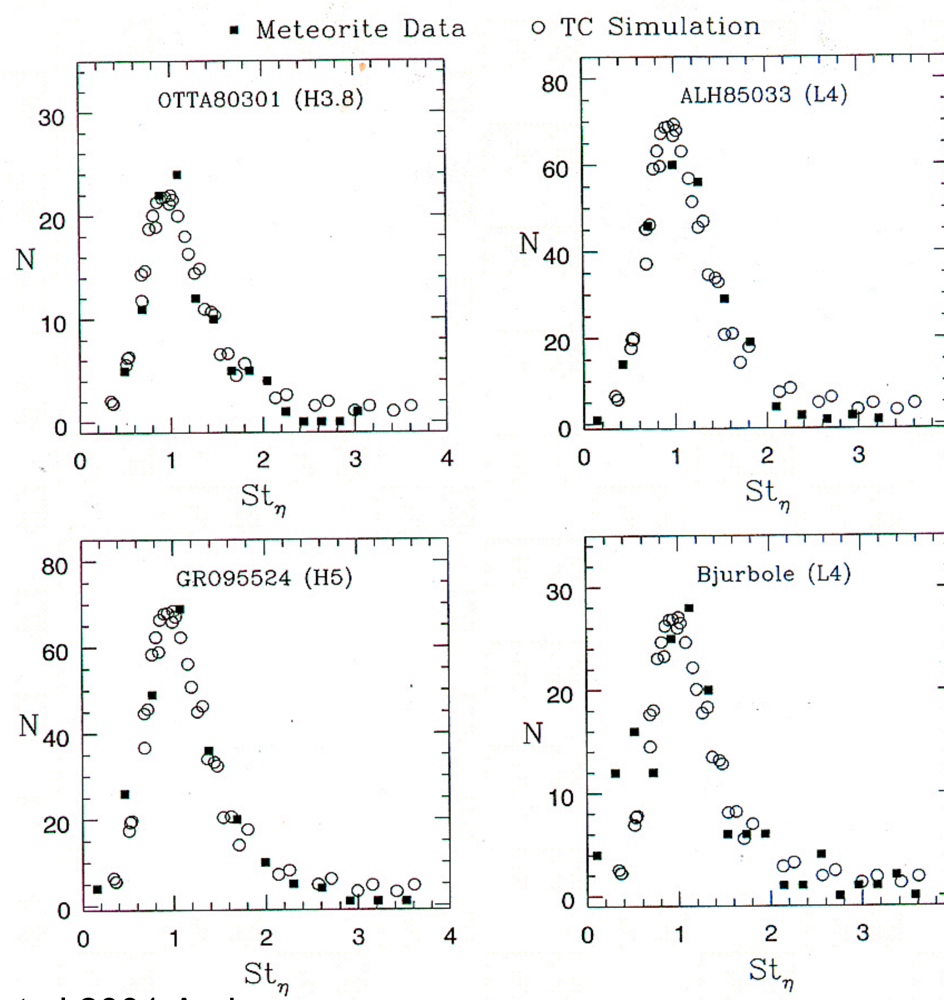
Both could operate independently in the same environment
Both have issues to overcome

Turbulent Concentration - “fingerprints”

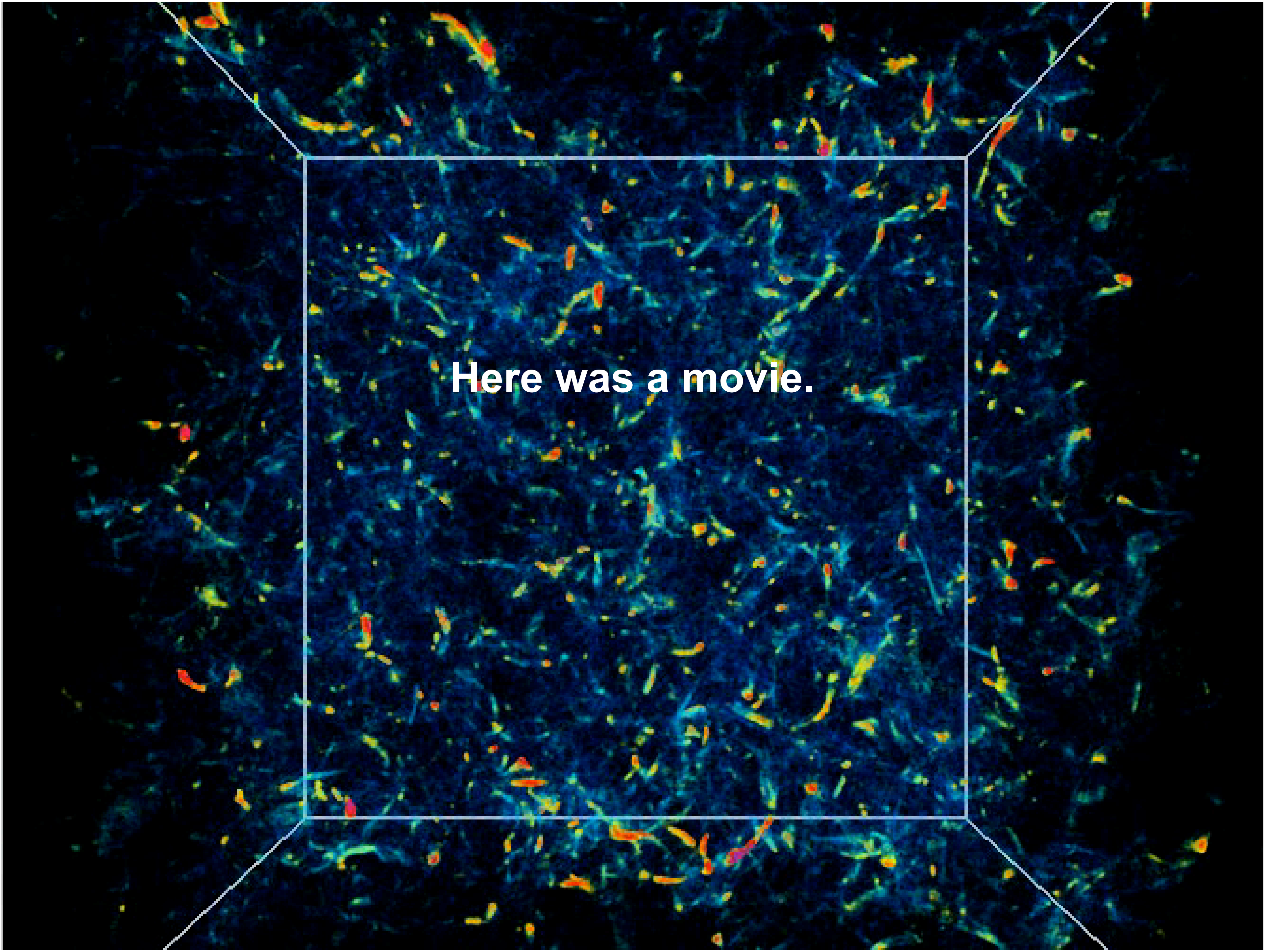
Predicted *size* and size *distribution* are a good match to chondrules if $St_\eta = 1$ at peak $(t_s = t_\eta)$ is assumed



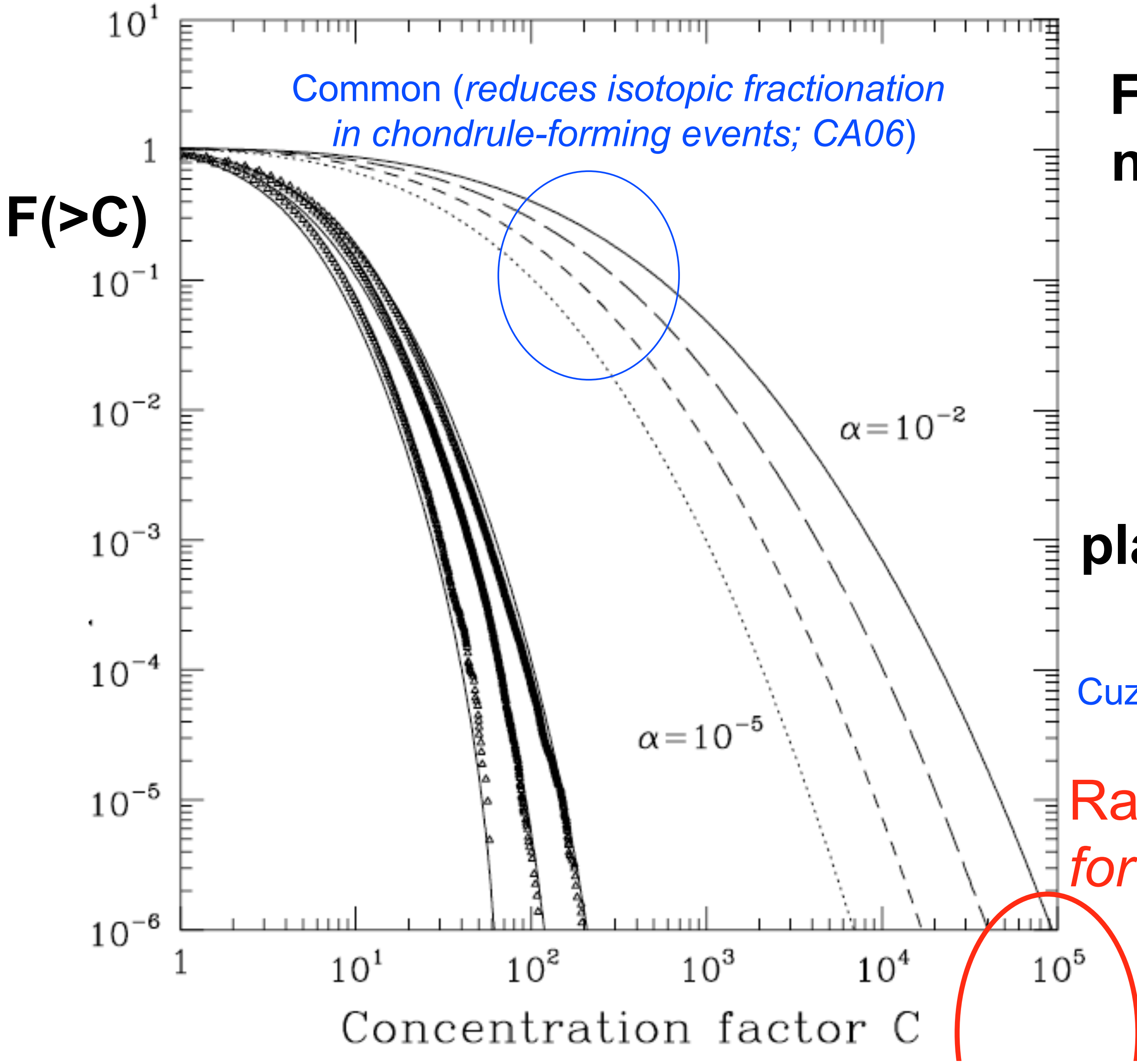




Cuzzi et al 2001 ApJ


Here was a movie.

Particle concentration factor (mass loading) follows a probability distribution F(C)



F(C) depends on nebula turbulent intensity α;

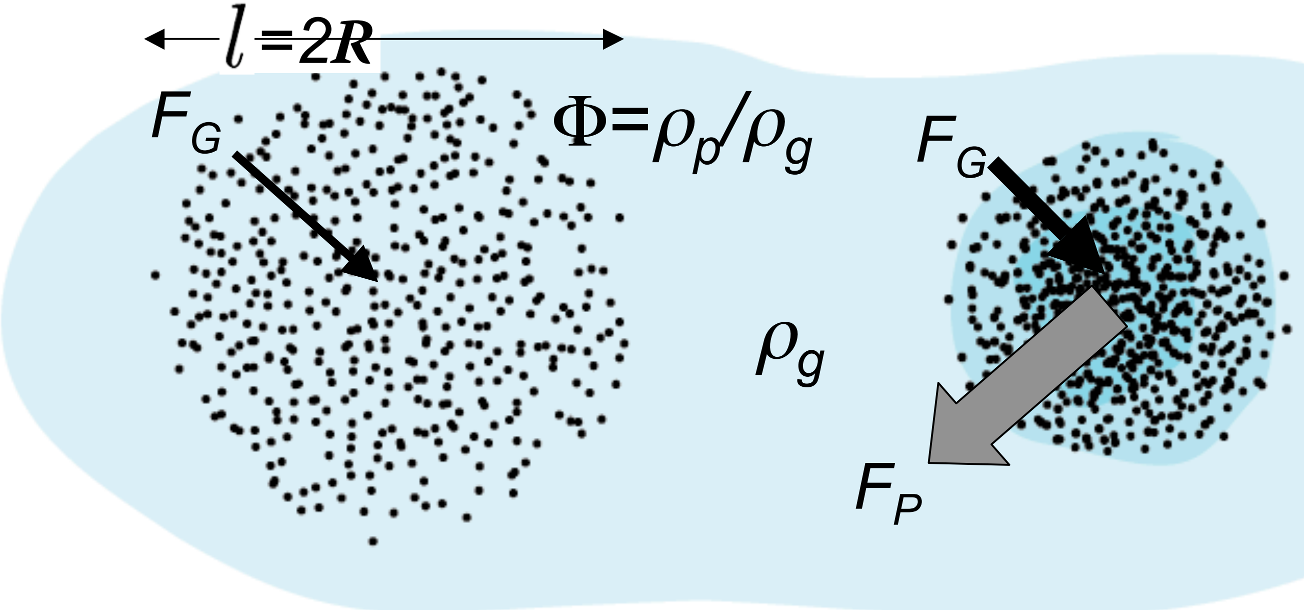
Different mass loadings play different roles

Cuzzi et al 2001 ApJ
Cuzzi & Alexander 2006 Nature

Rare (*dense enough for primary accretion*)

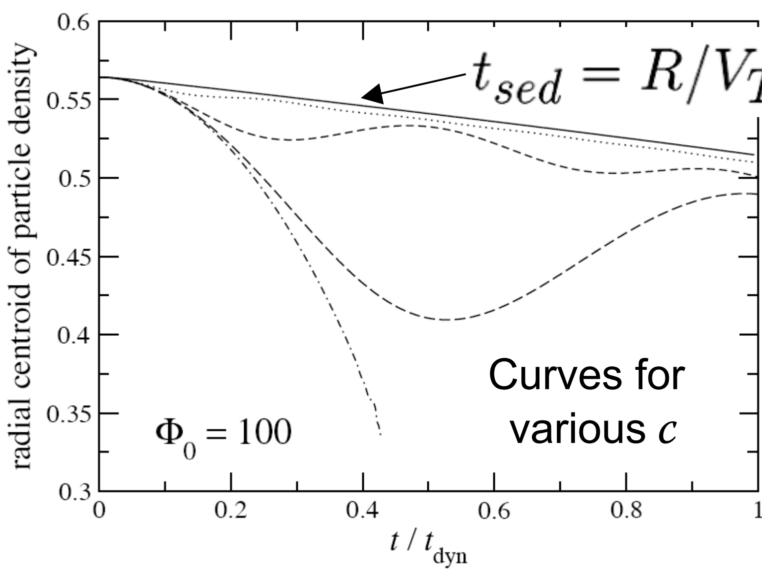
Gas pressure precludes GI for small particles!

(Sekiya 1983; but forgotten for 25 years)



for $F_G > F_P$:

$$\Phi > \frac{c/R}{(G\rho_g)^{1/2}}$$



$$t_{sed} = R/V_T = (12 G \rho_p t_s)^{-1} \sim 30 \text{ orbits}$$

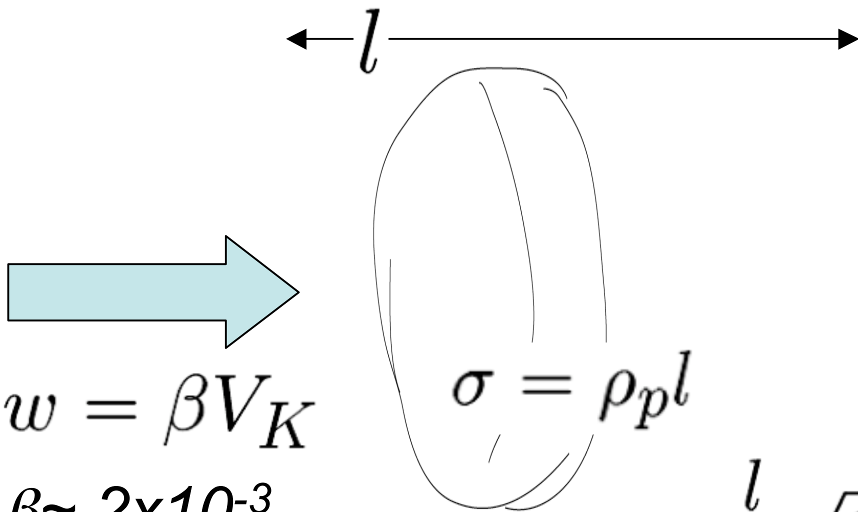
Classical GI: $\rho_p > 2\rho_R \sim M_\odot / 2a^3 \sim \Omega^2 / 2G$

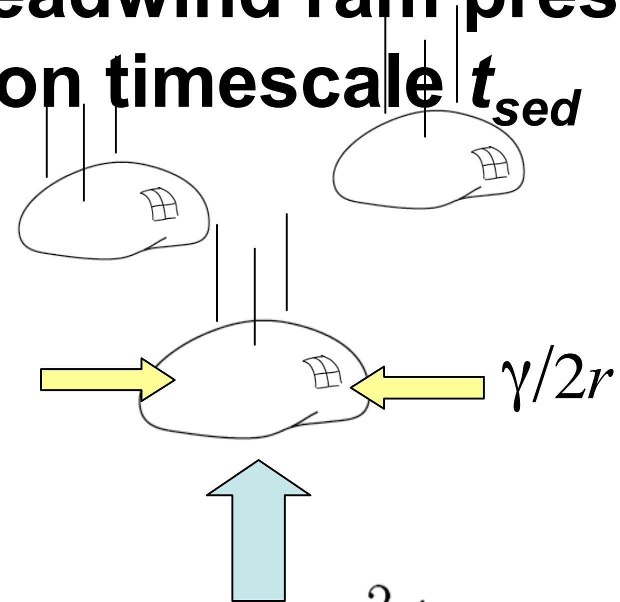
Safronov 1991, Goldreich & Ward 1973, Cuzzi et al 1993

$$\frac{\Phi}{\Phi_{clas}} = \frac{2c(G\rho_g)^{1/2}}{R\Omega^2} \sim 6000 \left(\frac{10^3 \text{km}}{R} \right)$$

Sekiya 1983, Cuzzi & Weidenschilling 2006

Dense clumps destroyed by headwind ram pressure on the slow sedimentation timescale t_{sed}





$$w = \beta V_K$$

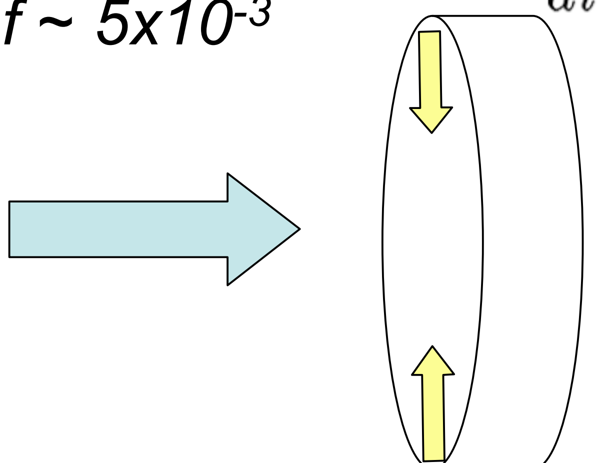
$$\sigma = \rho_p l$$

$\beta \sim 2x10^{-3}$

$f \sim 5x10^{-3}$

$$t_{dis} = \frac{l}{w}\sqrt{2\Phi}$$

$$P_g = \rho_g w^2/2$$



$$We = \frac{\rho_g w^2}{\gamma/2r} < We^*$$

$$We_G = \frac{\rho_g w^2}{2G\Phi^2\rho_g^2 l^2} < \mathcal{O}(1)$$

$$G\sigma^2 = G(\rho_p l)^2 = G(\Phi\rho_g l)^2$$

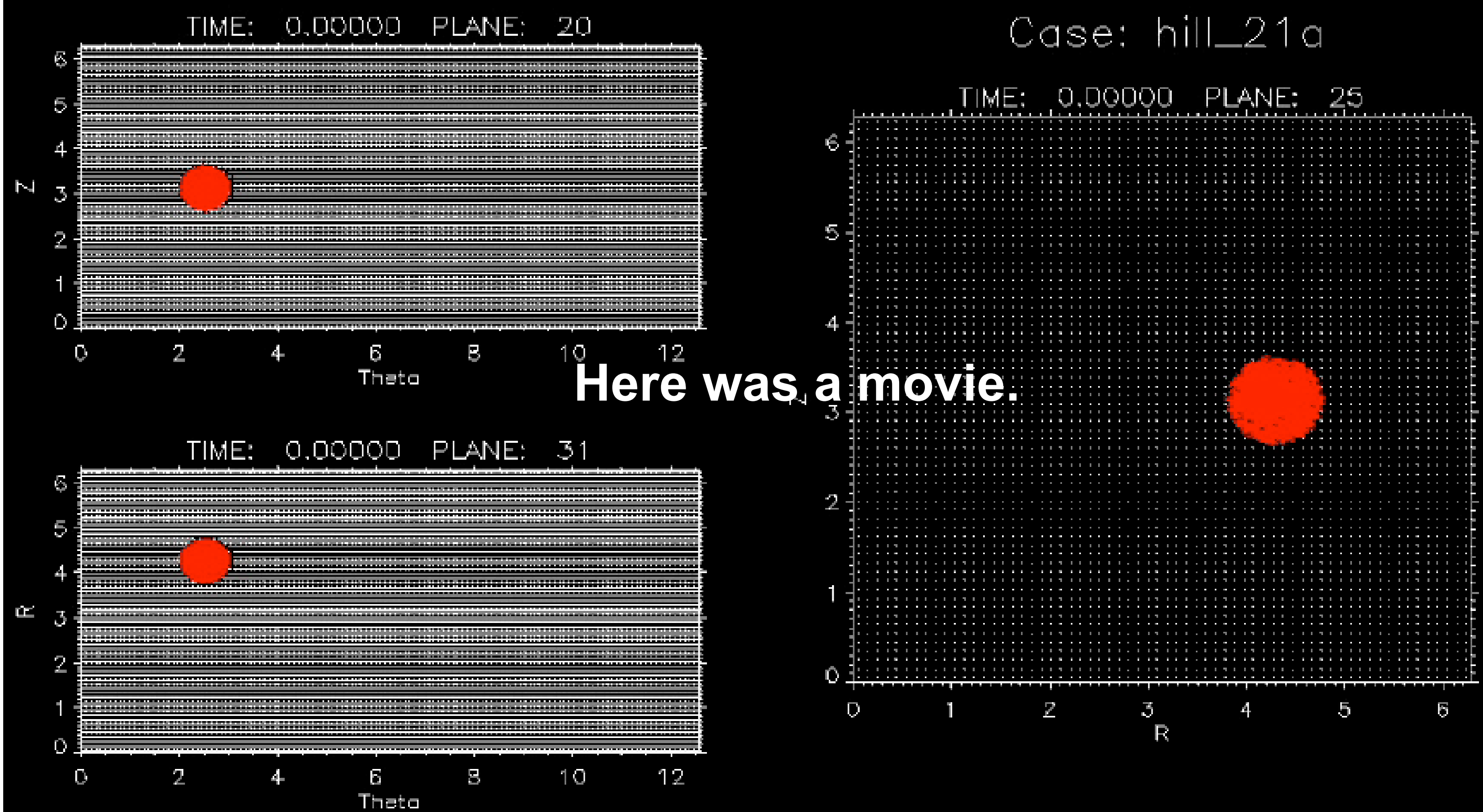
Solid object diam 20-50 km

Simulation equivalent to Φ=100, l=10^4 km, β=2×10^{-3}

without self-gravity

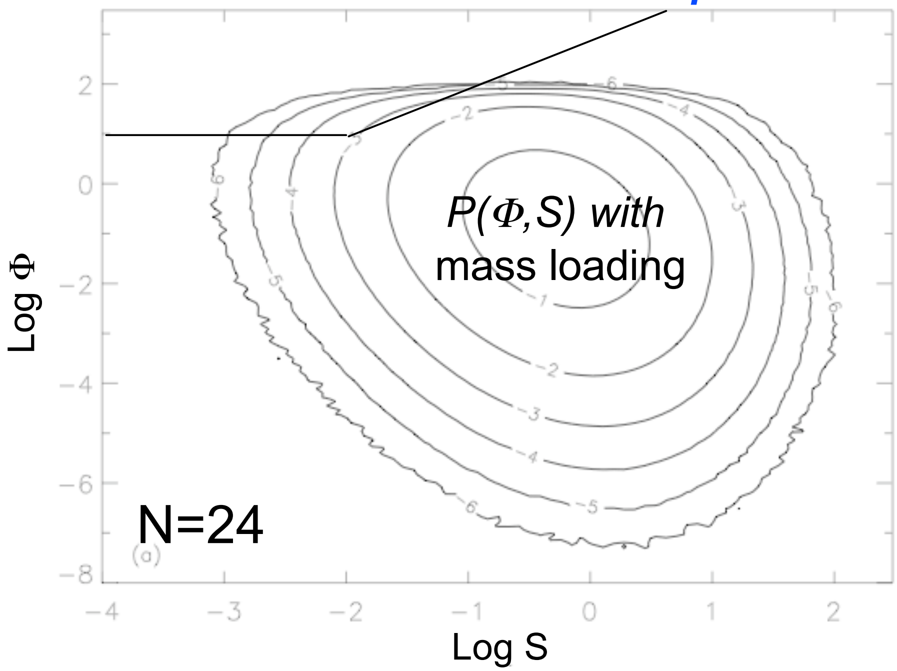
Here was a movie.

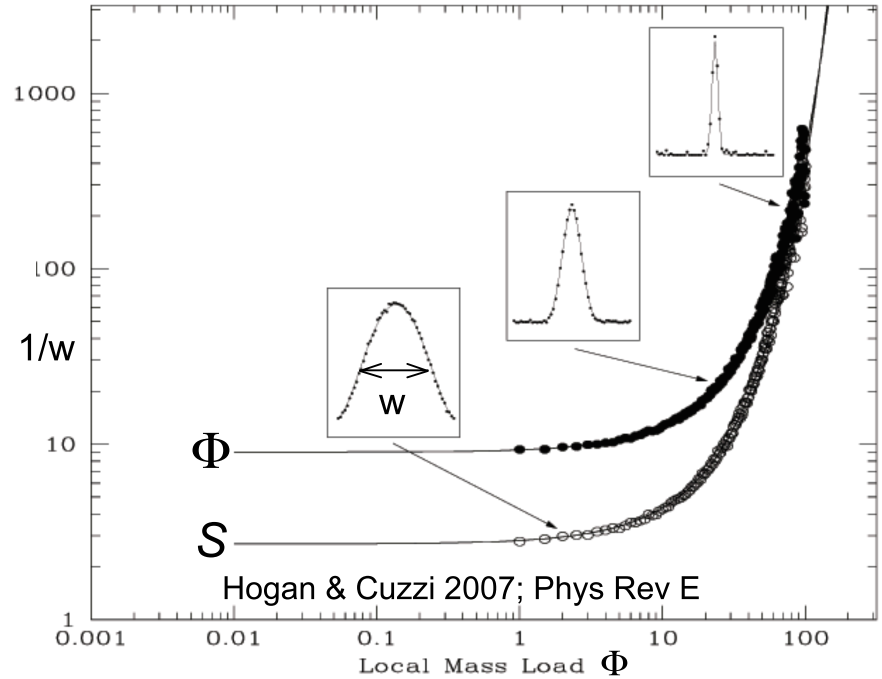
Simulation equivalent to Φ=100, l=10^4 km, β=$2\mathrm{x}10^{-3}$ *with* self-gravity; We_G criterion validated!



Determining the creation rate of suitable clumps at (Φ,l):

Cascade model of *particle-laden* turbulent concentration





Use multipliers to determine $P(\Phi,S)$ = Joint PDF of Φ and *vorticity S*

- includes known spatial anticorrelation of the two quantities.
- checked against exact 3D turbulence simulations; good agreement
- can be run to **far** higher *Re* than CFD simulations (*ie,* to nebula α)

Mass loading saturates $P(\Phi,S)$ *at* Φ ~100

$P(\Phi,S)$ then used to calculate

formation rate and mass of primary planetesimals

Summary of this primary accretion scenario

Nebula particulate mix may be slowly varying radially
but evolves with time (chemistry, isotopes, mass)

Local abundances of solids & vapor can be greatly enhanced
by rapid radial drift of “boulders” from further out

Chondrules are formed by heating in common dense clumps
which have concentration ~ hundreds of times “cosmic”

Rare, very dense clumps become gravitationally bound
and sediment inwards to form 10-100km “sandpiles”

Sandpiles contain well-characterized, size-sorted particles
of size which depends on local gas density and α

Process can operate anywhere but “fingerprints” may be
less apparent where only fluffy aggregates exist

Statistical techniques are needed to assess whether
primary accretion “rate” satisfies constraints

Open issues and good areas for future work

Turbulence: MRI vs hydrodynamical production?
sporadic and/or layered turbulence?
can turbulence be measured observationally?

Lab experiments on strength/compressibility of aggregates
(size distributions, tensile/compressive; etc)

Coupled growth / drift / radiative transfer / thermal modeling
possible applications to inner and outer nebula problems

Interferometric/spectroscopic observations of early disks
evidence for unusual vapor abundances inside EFs?

Primary accretion: behavior of dense clumps in turbulence
(collision? disruption/coagulation? statistics?)